# CARBON, EVAPOTRANSPIRATION AND ENERGY BALANCE DYNAMICS OF POTENTIAL BIOENERGY CROPS COMPARED TO COTTON IN THE SOUTHERN GREAT PLAINS

A Dissertation

by

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## ABSTRACT

The Southern Great Plains has potential to produce bioenergy crops on a large scale. However, the potential environmental impact of large scale production of bioenergy crops on carbon, evapotranspiration (ET) and energy dynamics of the region are not understood. This study focuses on land use change associated with bioenergy crops production in the Southern Great Plains and its implication on on-site carbon, energy and ET balances. The carbon and energy balance of two potential bioenergy crops, irrigated sorghum (*Sorghum bicolor* L.) and dryland old world bluestem (OWB) (*Bothriochloa bladhii* L.), were assessed and compared with conventional irrigated and dryland cotton (*Gossypium hirsutum* L.) cropping system of the region. Experiments were conducted on four large producer fields (irrigated sorghum, dryland OWB, irrigated and dryland cotton) in the Texas High plains region. An eddy covariance system was installed in the middle of each field. Continuous measurement of carbon dioxide, latent heat, and sensible heat exchange between plant canopy and atmosphere were made using eddy covariance systems. In addition, net radiation, soil heat flux, air temperature, soil temperature, relative humidity, vapor pressure deficit, soil moisture, photosynthetically active radiation (PAR), and total solar irradiance were measured at each site. Our results showed that mean seasonal net carbon uptake of the sorghum was -615.7 g C $m^{-2}$, OWB was -334.9 g C $m^{-2}$, irrigated cotton was -136.3 g C $m^{-2}$ and dryland cotton was -104.4 g C $m^{-2}$. Similarly, mean seasonal ET from sorghum was 480.4 mm, OWB was 384.4 mm, irrigated cotton was 462.9 mm and dryland cotton was

323.2 mm. At an annual scale both sorghum and OWB acted as robust sinks of carbon, whereas cotton cropping systems remained source of carbon. Mean annual net ecosystem exchange of carbon in was -248.1 g C $m^{-2}$ in sorghum, -284.9 g C $m^{-2}$ in OWB, 112.6 g C $m^{-2}$ in irrigated cotton, and 37.2 g C $m^{-2}$. At an annual scale irrigated crops recorded higher ET than total annual rainfall. It was also observed that bioenergy crops registered greater ecosystem water use efficiency (3.3 g C $kg^{-1}$ $H_2O$ in sorghum and 2.8 g C $kg^{-1}$ $H_2O$ in OWB) than cotton (2.0 g C $kg^{-1}$ $H_2O$ in irrigated cotton and 1.4 g C $kg^{-1}$ $H_2O$ in dryland cotton), indicating more sustainability in terms of water usage by bioenergy crops. Among bioenergy crops, sorghum due to irrigation performed better than OWB in terms of carbon assimilation. However, smaller annual ET from OWB than annual rainfall indicated greater groundwater recharge potential. Higher growth rates in C4 bioenergy crops were responsible for their high net carbon sinking capacities. Overall, land use shift from cotton to bioenergy crops was found to be more sustainable in terms of carbon sequestration and water usage.

## DEDICATION

I dedicate this dissertation to my family. Their support and encouragement always motivated me to pursue higher education. They have been a big inspiration to me throughout my journey from under-graduation to PhD.

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# CHAPTER I

# INTRODUCTION

According to the current renewable fuel standard (RFS), the United States will require 136 billion liters of biofuels per year by 2022 (USDA, 2010). The RFS mandates that out of this 136 billion liter target, 80 billion liters will need to be produced from second generation biofuels (USDA, 2010). Second generation biofuels are mainly produced from the by-products of first generation crops or from biomass crops grown with less-intensive agricultural activities conducted on marginal lands using substantially reduced resource inputs. In the 2010 Biofuels Strategic Production Report, the USDA has identified regions in the United States that have a comparative advantage of producing specific bioenergy crops based on the prevailing cropping systems, their yields and the current producer interest in growing these crops. Approximately 50% of the 80 billion liters target of second-generation biofuels is estimated to be produced from the southeast region of the United States including the Southern Great Plains. However, environmental impacts and long-term sustainability of large scale production of bioenergy crops in the Southern Great Plains has not been addressed adequately.

The Texas High Plains region in the Southern Great Plains is a major agricultural region in the United States (Fig. 1.1). This region is semi-arid with a long-term (1911-2005) mean annual rainfall of about 465 mm (Allen et al., 2008). The Texas High Plains

region was dominated by shortgrass prairie prior to the discovery of the vast underground Ogallala Aquifer (Gould, 1975; Allen et al., 2008). Availability of water for irrigation from the Ogallala Aquifer transformed this semi-arid region into one of the most intensively cultivated agricultural production regions in the U.S. (Allen et al., 2008; Rajan et al., 2014). In fact, the Southern Great Plains is the largest producer of cotton (*Gossypium hirsutum* L.) in the U.S. (Attia et al., 2015). Grain sorghum (*Sorghum*

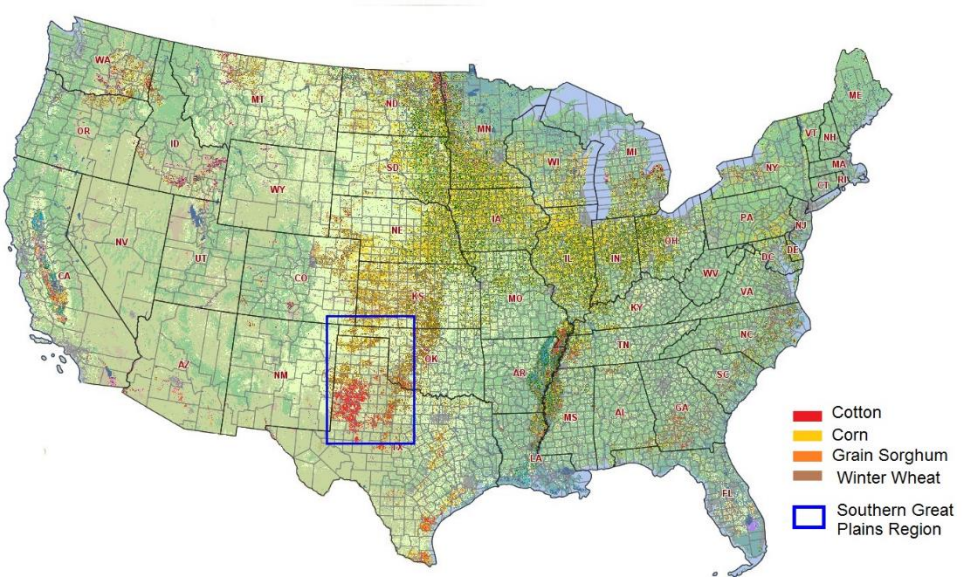


**Figure 1.1: Southern Great Plains region and major cropping systems. Reprinted from: USDA-National Agricultural Statistics Service CropScape- Cropland Data Layer. Copyright © Center for Spatial Information Science and Systems 2009-2016**

*bicolor* L.), corn (*Zea mays* L.), and winter wheat (*Triticum aestivum* L.) are other major crops in the region. More than 95% of the water pumped from the Ogallala Aquifer is currently used for irrigation of agricultural crops (Nair et al., 2013). However, excessive

extraction of water for agricultural use has depressed the water table of the Ogallala Aquifer by over 30 m in most parts of the Southern Great Plains (Rajan et al., 2015). The declining water for irrigation in this region poses big challenges to the production of first generation biofuels such as corn as it has high water requirement compared to other cellulosic bioenergy crops.

Continuous cotton under conventional tillage has been a dominant row cropping system in the Southern Great Plains for several decades (Fig. 1.1) (Acosta-Martinez et al., 2010). Low returns of organic matter from cotton cropping systems has depleted the organic matter reserves of the soils in Southern Great Plains and declined the soil quality (Moore et al., 2000; Wright et al., 2008; Allen et al., 2008; Acosta-Martinez, 2010). Soil organic matter accumulation is important for soil health as it improves soil structure, prevents soil erosion, improves infiltration and water holding capacity, and sequesters atmospheric carbon dioxide (Lal, 2004). Land use change from conventional cropping systems to bioenergy cropping systems will have major environmental implications. Several recent studies have reported the net carbon sinking capacity of annual and perennial bioenergy crops at ecosystem scale in different parts of North America (Zeri et al., 2011; Wagle et al., 2015; Oikawa et al., 2015; Eichelmann et al., 2016). Several studies have reported improved soil organic matter status with bioenergy crops depending upon management practices and amount of residues left on the surface after harvest (Halvin et al., 1990;Polley, 1992; Tolbert et al., 2002; Cotton, 2013b; Meki et al., 2013). Similarly, conversion of croplands to perennial grasslands can reclaim the soil organic carbon and improve soil health over time depending upon climatic conditions

(Burke et al., 1988; McLauchlan et al., 2006). However, more investigation is necessary to understand the carbon dynamics as a result of land use change from cotton to bioenergy crop production systems in the Southern Great Plains.

Another major implication of land use change in the Southern High Plains to bioenergy crops will be on surface energy balance. Surface energy fluxes include the turbulent fluxes of latent heat or evapotranspiration (ET), sensible heat, and solar and terrestrial radiative fluxes (Rajan et al., 2010). The differences in canopy structure and background soil characteristics affect how incoming solar energy is partitioned among various components of the energy balance, which can be written as:

$$R_n = LE + H + G + M + S$$

where $R_n$ is the net radiation, LE is the latent heat flux, H is the sensible heat flux, G is the soil heat flux, M is the metabolic energy associated with plant photosynthesis and respiration, and S is the heat storage in the above-ground biomass. Land use changes can alter surface characteristics such as vegetation cover, surface roughness, albedo, and soil moisture (Kueppers et al, 2008). Changes in one or more of these variables can significantly alter the fluxes and energy balance, which can ultimately lead to changes in local and regional climate. If large areas of the Southern Great Plains are converted to second-generation biofuel feedstocks, it is possible that such a change will significantly impact the surface energy fluxes in the region.

Similar to energy fluxes, surface and near-surface hydrological processes are also modified due to changes in crop characteristics and management practices. Cotton,

biomass sorghum, and perennial grasses have unique leaf distribution and density characteristics which, in turn, affect the micro-climatic regimes within the plant canopy. The denser canopy of perennial grasses limits the amount of radiation reaching the ground surface, thereby affecting the soil evaporation component of ET (Schulze et al., 1994; Rajan et al., 2010). Le et al. (2011) reported that, under current climatic conditions, land use change from corn to bioenergy crops such as switchgrass and *Miscanthus* could increase the seasonal ET by 56% and 36%, respectively, in the Midwest. Similar results were also reported for the Midwest region by Hickman et al. (2010), using the residual energy balance method, and by VanLoocke et al. (2010) using modeling. The potential for biofuel crops such as perennial grasses and biomass sorghum to alter the regional hydrologic cycle by replacing the immense acreage of cotton in the Southwestern Cotton Belt region is unknown and thus needs to be investigated.

This study includes results from the on-site research conducted on bioenergy and conventional cropping systems in the Southern Great Plains. We investigated carbon, energy and evapotranspiration dynamics of potential bioenergy cropping systems and conventional cotton cropping systems. This dissertation consists of six chapters.

- Chapter I provides introduction and background of the study.
- Chapter II is dedicated to the assessment of seasonal dynamics of carbon and ET of high biomass forage sorghum, its biofuel generation capacities and potential to establish itself as a bioenergy crop in the Southern Great Plains. Phenological

and environmental controls over seasonal carbon dynamics of sorghum are also discussed in this chapter.

- Chapter III compares seasonal and inter-annual on-site carbon dynamics of a potential annual (sorghum) and perennial (Old World Bluestem) bioenergy crops in the Southern Great Plains. In addition to growth habits and environmental controls, potential environmental impacts of large scale production of these crops are also discussed in this chapter. Biomass production and possible ecosystem services of both bioenergy crops are also discussed in this chapter.
- Chapter IV assesses and compares the carbon dynamics of bioenergy crops with irrigated and dryland cotton cropping systems. Possible impacts of land use change from cotton cropping systems to bioenergy cropping systems on biosphere-atmosphere carbon exchanges are discussed in this chapter.
- Chapter V assesses and compares seasonal and inter-annual energy balance, ET and water use efficiency (WUE) of all the crops studied as part of this dissertation research in the Southern Great Plains. Potential implications of land use change on ET, energy balance and water use efficiency in the Southern Great Plains are also discussed.
- Chapter VI provides overall summary of this research and recommendations for future work.

# CHAPTER II

# SEASONAL VARIABILITY IN EVAPOTRANSPIRATION AND NET ECOSYSTEM CARBON DIOXIDE EXCHANGE OF HIGH BIOMASS FORAGE SORGHUM IN THE SOUTHERN GREAT PLAINS

## INTRODUCTION

Despite recent low oil prices, fuel ethanol production in the U.S. has increased from 10.60 Billion Gallons (BG) in 2009 to 14.70 BG in 2015 (RFS, 2016). Corn (*Zea mays* L) has been the primary feedstock for fuel ethanol production in the U.S. Approximately, 850 million gallons (MG) of U.S. fuel ethanol was exported to more than 50 countries in 2015 (RFS, 2016). Although U.S. is the largest exporter of fuel ethanol in the world, it also imported 96 MG of ethanol in 2015. Majority of this imported ethanol came from Brazil. The main reason for the import was because the Renewable Fuel Standard (RFS) and the Low Carbon Fuel Standards (LCFS) of California and other states specify the use of biofuels with low greenhouse gas (GHG) emissions (Whistance et al., 2017). Based on life cycle analyses, GHG emissions from sugarcane (*Saccharum spp.*) cropping systems in Brazil are considered to have less GHG emissions compared to corn cropping systems in the U.S., thus promoting its import. The RFS statutory requirement for renewable fuel production is 30 BG in 2020, of which at

least 35% of total renewable fuels must be produced from cellulosic biofuels with low GHG emissions.

Cellulosic biofuels are considered second generation biofuels and are produced from ligno-cellulosic biomass feedstock using advanced conversion technological processes (Naik et al., 2010). The main cellulosic biomass feedstocks include agricultural residues and dedicated herbaceous and woody energy crops such as switchgrass (*Panicum virgatum*), Miscanthus, biomass sorghum (*Sorghum bicolor* L), and hybrid poplar (*Populus deltoids* × *Populus trichocarpa*). Many cellulosic bioenergy crops are ideal candidates for growing in the Southern Great Plains due to their adaptation to water-limited and semi-arid environmental conditions. For example, switchgrass is a cellulosic biofuel feedstock adapted to the environmental conditions in the Southern Great Plains (Sanderson et al., 2006; Jefferson and McCaughey, 2012; Chen et al., 2016). Another potential bioenergy crop that is gaining popularity in the Southern Great Plains is sorghum. Several studies have reported the drought tolerance and high WUE characteristics of biomass and forage sorghums in the Southern Great Plains (Hao et al., 2014; Chen et al., 2016; Wagle et al., 2015; Yimam et al., 2015). In addition to agronomic characteristics such as high WUE and high biomass production, physical and chemical properties of the feedstocks also play major roles in determining their suitability for biofuel production (Corredor et al., 2009; Karmakar et al., 2010; Atabani et al., 2013). The brown midrib (bmr) cultivars of forage sorghum have lower lignin content, and hence are more suitable for ethanol production as lignin tends to prevent the enzymes from accessing cellulose (Corredor et al., 2009; Dien et al, 2009;

Sattler et al., 2010). In addition, forage sorghum is cheaper to produce than corn. These attributes promote the use of forage sorghum for biofuel production (Shoemaker and Bransby, 2010). Several new bmr cultivars of forage sorghum have already been successfully introduced in the Southern Great Plains region.

Significant changes in land use from conventional cropping systems to second generation cellulosic cropping systems such as biomass or forage sorghum have several environment-related implications. Changes in land surface properties and management practices due to land use change to cellulosic biofuel crops can significantly affect net ecosystem $CO_2$ exchange (NEE) and evapotranspiration (ET) (Claussen et al., 2001; Rydsaa et al., 2015). In recent years, eddy covariance systems have been increasingly used for direct measurements of NEE and ET from various ecosystems (Baldocchi, 2003; Reichstein et al., 2007; Foken et al., 2012). Scientists have established networks of experimental sites such as Ameriflux with eddy covariance systems for measuring NEE, ET and energy exchange in key ecosystems in North America (Law, 2007). Data from these experimental sites are critical for gaining a proper understanding of regional and global carbon and hydrologic cycles. However, very few studies have been conducted investigating ET and carbon flux dynamics of biomass sorghum (Wagle, 2016). In this three-year study (2013 to 2015), we examined half-hourly, daily, and seasonal ET, and carbon flux dynamics (NEE, Gross Primary Production/GPP and Ecosystem Respiration/$R_{eco}$) of annual sorghum in the Southern Great Plains. In addition, we studied energy partitioning and ecosystem WUE. Our results provide further insights

into the dynamics of carbon fluxes and ET for this lesser studied, yet crucial, cellulosic biofuel cropping system.

## MATERIALS AND METHODS

### Study Site

The study was conducted in a farmer's center-pivot irrigated field planted to high biomass forage sorghum for commercial seed production. The field was located approximately 4.5 km northeast of Plainview, TX in the Southern Great Plains region (34°12'34.70'' N and 101°37'50.85'' W, 1100 m elevation). The total area of the center pivot field was 50 ha and sorghum was planted to half of the area (25 ha). Remaining half of the field was planted to cotton (*Gossypium hirsutum* L). The sorghum cultivar planted was Surpass XL *bmr*. The crop was planted on 20 May in 2013 and 2014. Heavy rains in 2015 delayed planting, thus the crop was planted on June 4 (DOY 155) that year. In all three years, the seeding rate was the same, 4.5 lbs $ac^{-1}$. However, the row spacing was narrower in 2014 (50 cm) compared to 2013 and 2015 (100 cm). The field was supplied with 150 kg N $ha^{-1}$ via Urea (32-0-0) broadcasting in spring before planting. In addition, 30 kg $P_2O_5$ $ha^{-1}$ was also applied prior to planting. For the first 40 days, the field was supplied with approximately 19 mm of water during each irrigation event. For the rest of the season, the field was irrigated with 38 mm of water during each irrigation event. Overall, the field was supplied with 400 mm of irrigation water in 2013 (12 irrigations) and 2014 (12 irrigations), and 267 mm of irrigation water in 2015 (7 irrigations). The field was harvested for seed on 8 October in 2013, 14 October in 2014, and 1 October in 2015. The growing season was 141, 147, and 119 days long in 2013,

2014, and 2015, respectively. The field was disked in early spring to incorporate residues from cotton. The field was disked again before planting and was cultivated twice in June to control weeds. The major soil mapping unit at the study site is Pullman Clay Loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with 0 to 1% slope.

**Eddy Covariance and Ancillary Data Collection**

Continuous measurements of $CO_2$ and water vapor were made using an eddy covariance flux tower established in the field at the beginning of planting. The height of the instrument tower was adjusted periodically to maintain a distance of 1.5 m from the top of the canopy and eddy covariance instruments. The movement of the irrigation system did not interfere with data collection as the height of the center-pivot system was over 3 m. Wind velocity, $CO_2$, and water vapor concentrations were measured using IRGASON, which is an integrated open-path infrared gas analyzer (IRGA, Model EC-150, Campbell Scientific) and sonic anemometer (Model CSAT-3A, Campbell Scientific) system. These instruments were set up facing southwest (into the prevailing wind direction). Other environmental variables measured included air temperature ($T_{air}$) and relative humidity (RH) (HMP50, Campbell Scientific), net radiation (Kipp & Zonen NR-Lite net radiometer), photosynthetic photon flux density (PPFD) (LI-200SL quantum sensor, LI-COR), global irradiance (LI-190SB pyranometer, LI-COR), precipitation (TE525 rain gauge, Campbell Scientific), soil temperature ($T_{soil}$) at 4 cm below the surface (TCAV averaging soil thermocouples, Campbell Scientific), and soil volumetric water content at 4 cm below the surface (CS-616 water content reflectometer, Campbell Scientific). The IRGA and net radiometer surfaces were cleaned weekly

according to the manufacturers' guidelines to avoid accumulation of dust. Soil heat flux ($G_{8cm}$) was measured using self-calibrating soil heat flux plates (HFPSC-01, Hukseflux, Campbell Scientific, Logan, UT) at 8 cm depth from the soil surface. Soil heat storage above the heat flux plate was calculated using the following equation and was added to the measured soil heat flux at 8 cm to obtain soil heat flux at the surface (G) (Eq. 2.1).

$$G = G_{8cm} + S \quad [2.1]$$

$$S = \frac{\Delta T_s C_s d}{t} \quad [2.2]$$

where S is heat storage, $\Delta T_s$ is change in surface soil temperature, $d$ is depth of soil in meters above soil heat flux plate, $C_s$ is the heat capacity of moist soil, and $t$ is time in seconds. Heat capacity of soil in Eq. 2 can be calculated using bulk density ($\rho_b =$ 1.3 gm $cm^{-3}$), volumetric water content ($\theta_v$), density of water ($\rho_w = 1000\ kg\ m^{-3}$), heat capacity of water ($C_w = 4.2\ kJ\ kg^{-1}K^{-1}$), and heat capacity of dry soil ($C_d$ = 840 J $kg^{-1}$ $K^{-1}$) as follows:

$$C_s = \rho_b C_d + \theta_v \rho_w C_w \quad [2.3]$$

Data from the CSAT3A sonic anemometer and EC150 system were measured at 10-Hz sampling rate using a CR3000 datalogger (Campbell Scientific). All other environmental variables were measured at 5 seconds interval. The datalogger was programmed to calculate and save 30-min average values of all environmental variables. The raw 10-Hz wind velocity, $CO_2$, and water vapor data were saved for further post-processing and analysis of NEE, GPP, $R_{eco}$, ET and H.

Supporting plant measurements collected include height, leaf area index (LAI), and biomass. Height was measured from the soil surface to the top of the canopy. Plant samples were taken randomly from the field to measure leaf area index (LAI) and biomass. Plants were stored in an ice chest in the field and leaf area was measured (after separating leaves from shoots) using a leaf area meter (Model LI-3100, Licor Biosciences, Lincoln, NE) immediately after they were brought to the laboratory. Plant density (number of plants per $m^2$) and leaf area were used to calculate the LAI.

**Eddy Covariance Data Processing and Analysis**

Using the eddy covariance method, half-hourly fluxes of $CO_2$ and latent heat (LE) were calculated as the covariance between fluctuations from the mean vertical wind speed and corresponding fluctuations of $CO_2$ and water vapor. The sensible heat was calculated similarly using vertical wind speed and air temperature. We used the open source EddyPro 4.0 software (LI-COR Biosciences, Lincoln, NE) to compute half-hourly fluxes using the eddy covariance method. Calculation of fluxes requires a series of operations including raw data filtering and applications of algorithms for calculating and correcting fluxes. Some of these corrections include spike removal, spectral corrections for flux losses (Moncrieff et al., 1997), and corrections for air density fluctuations (Webb et al., 1980). Eddy Pro assigns quality flags based on widely used tests for steady state and turbulence (Göckede et al., 2008). The flag '0' indicates high quality fluxes and '1' indicates intermediate quality fluxes. All poor quality fluxes are flagged as '2'. The processed half-hourly fluxes were subjected to additional quality control before gap filling. In addition to 30 min data that were flagged as '2', data were discarded during

precipitation, equipment maintenance, and low turbulence conditions (when the friction velocity was <0.10 m $s^{-1}$).

All missing 30 min flux data (NEE, LE and H) were filled using the online CarboEurope and Fluxnet eddy covariance gap-filling tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/). This online tool uses methods similar to those described in Falge et al (2001) and Reichstein et al (2005). All missing 30 min fluxes were replaced by the average value under similar meteorological conditions within a time-window of 7 days. This window was expanded to ±14 days in case similarity in meteorological conditions were not present within 7 days window. This online tool also provided estimations of half-hourly GPP and $R_{eco}$. Night-time NEE values represent $R_{eco}$. Daytime $R_{eco}$ was estimated using short-term temperature sensitivity equations developed between night-time NEE measurements and corresponding soil temperature ($T_{soil}$) measurements made at the 4-cm depth. The GPP was estimated as the difference between $R_{eco}$ and NEE.

We examined energy balance closure to assess the quality of eddy covariance estimates of LE and H (Wilson et al., 2002). The difference between $R_n$ and G represents the available energy at the surface. Assuming negligible heat storage within the canopy and net horizontal advection of energy, the energy balance can be described in Eq. 2.4:

$$R_n - G = LE + H \qquad [2.4]$$

The sign convention used for $R_n$ and G are positive when the flux is downwards and negative when the flux is upward. The sign convention used for LE, H and C fluxes

was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

### Evapotranspiration and Water Use Efficiency

The 30 min LE data was used to calculate ET using the following equation:

$$ET = \frac{LE}{\rho_w \lambda} \qquad [2.5]$$

where, $\rho_w$ density of water (1000 kg $m^{-3}$), and LE is the latent heat of vaporization (2.5 × $10^6$ J $kg^{-1}$). Ecosystem WUE ($WUE_{ECO}$) at monthly, and seasonal scales were calculated by dividing daytime cumulative GPP by daytime cumulative ET at monthly, and seasonal timescales, respectively.

## RESULTS AND DISCUSSION

### Energy Balance Closure

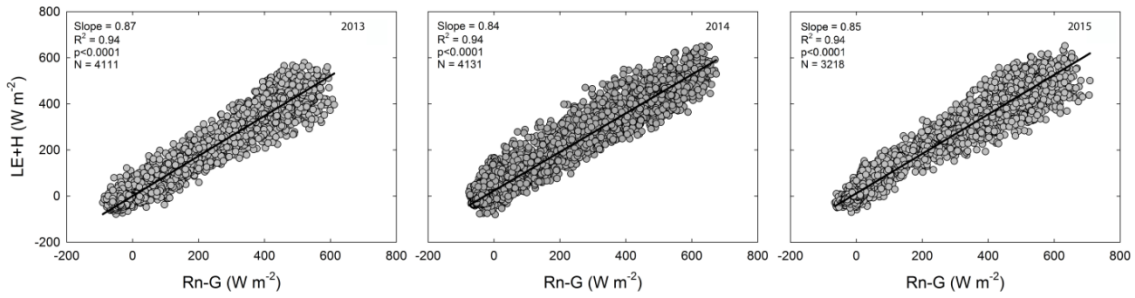


**Figure 2.1. Energy Balance Closure of Sorghum during growing season (July-September). High quality 30 minute values of latent heat (LE), Rn (net radiation), soil heat (G) and sensible heat (H) were used to calculate energy balance.**

Seasonal energy balance closure was calculated using half-hourly turbulent fluxes (LE and H) and available energy ($R_n$ and G) components. Data were included in the analysis only when all four measurements were available. The sum of half-hourly LE and H was strongly correlated to the sum of available energy ($R_n$-G) in all three years with an $R^2$ value of 0.94 (Fig. 2.1). The degree of surface energy balance closure is indicated by the slope of the linear regression line through these data. The slope of the regression lines were 0.87, 0.84 and 0.85 for 2013, 2014, and 2015, respectively, indicating that 84 to 87% of the variation in daily available energy ($R_n$-G) was accounted for by the sum of the turbulent energy fluxes (Fig. 2.1). This degree of energy balance closure at our site is similar to those reported in other studies. Foken (2008) reported that energy balance closure was in the range of 70 to 90% for a variety of ecosystems studied using eddy covariance measurements. Wagle and Kakani (2014) reported closure on the order of 77% for a biomass sorghum field in the Southern Great Plains. In our study, we did not use a correction factor to close the energy balance because the causes of underestimation of eddy covariance fluxes are not fully understood and are continually debated (Aubinet et al., 2000; Twine et al., 2000).

**Meteorological Conditions and Plant Phenology**

Weekly average environmental data from the site is presented in Figure 2.2. The 2013 growing season precipitation (241 mm) was less than the precipitation received in 2014 (328 mm) and 2015 (271 mm). The precipitation distribution over the growing season also varied across the three growing seasons. This resulted in differences in weekly average VPD and solar irradiance among the three study years. Weekly average

VPD over the course of the growing season ranged from 0.42 to 2.4 kPa in 2013, 0.33 to 1.7 kPa in 2014 and 1.1 to 1.9 kPa in 2015. Weekly average VPD was the lowest in 2014, year with the highest growing season precipitation. Dry and clear sky conditions in Late May and early June in 2013 caused VPD to peak above 1.5 kPa that year. During the peak growing months in 2013 and 2014, VPD dropped to below 1.5 kPa on most days. However in 2015, less precipitation received during the peak growing months (July and August) resulted in high VPD (above 1.5 kPa) on most days.

Weekly averages of air and soil temperature at 4 cm depths were closely correlated (R = 0.91 in 2013 and 2014 and R = 0.84 in 2015). Early in the season (May and June), average $T_{soil}$ was slightly higher than $T_{air}$ which decreased to below $T_{air}$ later in the season. Weekly average $T_{air}$ during study period ranged from 17.5 to 26.3 $^{o}$C in 2013, 14.1 to 26.1 $^{o}$C in 2014, and 19.8 to 26.4 $^{o}$C in 2015. Average $T_{air}$ for the growing season was 23.2 $^{o}$C in 2013, 21.9 $^{o}$C in 2014, and 23.9 $^{o}$C in 2015. In 2013 and 2015, seasonal average $T_{air}$ was close to the 30 year average temperature for the corresponding period (23.6 $^{o}$C). In 2014, seasonal average $T_{air}$ was approximately 2$^{o}$C less than the long-term average temperature. The average daily $T_{air}$ during the first week after planting in 2014 was approximately 8 $^{o}$C less than the $T_{air}$ during the corresponding period in 2013 (Figure 3a). Similar to $T_{air}$, the average daily $T_{soil}$ during the first week after planting in 2014 was approximately 6 $^{o}$C lower than the $T_{soil}$ during the corresponding period in 2013. Year 2014 also had low growing season average $T_{soil}$ (21.9 $^{o}$C) compared to 2013 (22.8 $^{o}$C) and 2015 (24.6 $^{o}$C). Spring 2014 was cooler than

normal and the low air and soil temperatures were due to late spring cold fronts passing over the region.

Measurements of phenological development were started once the plant stand was well established (June). In all three years, LAI changed rapidly during the growing season. The maximum LAI measured was 4.1 in 2013, 7.2 in 2014 and 5.1 in 2015 (Fig. 2.3). In all three years, LAI remained at its peak for approximately 2 weeks. Aboveground biomass (AGB) increased significantly from June to September. Peak AGB measured was 18 Mg $ha^{-1}$ in 2013, 24 Mg $ha^{-1}$ in 2014, and 21 Mg $ha^{-1}$ in 2015 (Fig. 2.4). The inter-annual variation in LAI and AGB was primarily due to the difference in plant population density. Plant emergence was higher in 2014 (11 plants $m^{-2}$) compared to that in 2013 (8.33 plants $m^{-2}$) and 2015 (9.25 plants $m^{-2}$). The higher plant density in 2014 was due to narrower row spacing. The influence of plant density on LAI and biomass has been reported in several previous studies (Steiner et al., 1986; Wall and Kanemasu, 1990; Kross et al., 2015).

The growth period of sorghum from emergence to maturity was approximately 100 days in our study. Even without a second harvest, the biomass production of sorghum at our study site was comparable to the seasonal biomass production of several other bioenergy crops in the U.S (Song et al., 2015). Researchers have reported the yield of biomass sorghum ranging from less than 10 Mg $ha^{-1}$ to over 30 Mg $ha^{-1}$, depending on the region and growing conditions. Oikawa et al. (2015) reported dry biomass production of sorghum ranging from 11.7 Mg $ha^{-1}$ to 16.2 Mg $ha^{-1}$ for three harvests between February and November in Arizona. In Florida, Singh et al. (2012) reported

19.4 Mg $ha^{-1}$ of AGB production for biomass sorghum. Cotton et al. (2013) reported dry biomass yield for forage sorghum ranging from 13.2 to 30.1 Mg $ha^{-1}$ in the Texas High Plains. These authors reported that the biomass yield varied depending upon irrigation level and cultivar characteristics. Results from our study suggest that high biomass forage sorghum could be a promising biomass crop in the semi-arid Southern Great Plains under irrigated conditions. The short growing period to reach maturity in this region also suggests ratooning and double-cropping possibilities with winter wheat or other short duration crops.

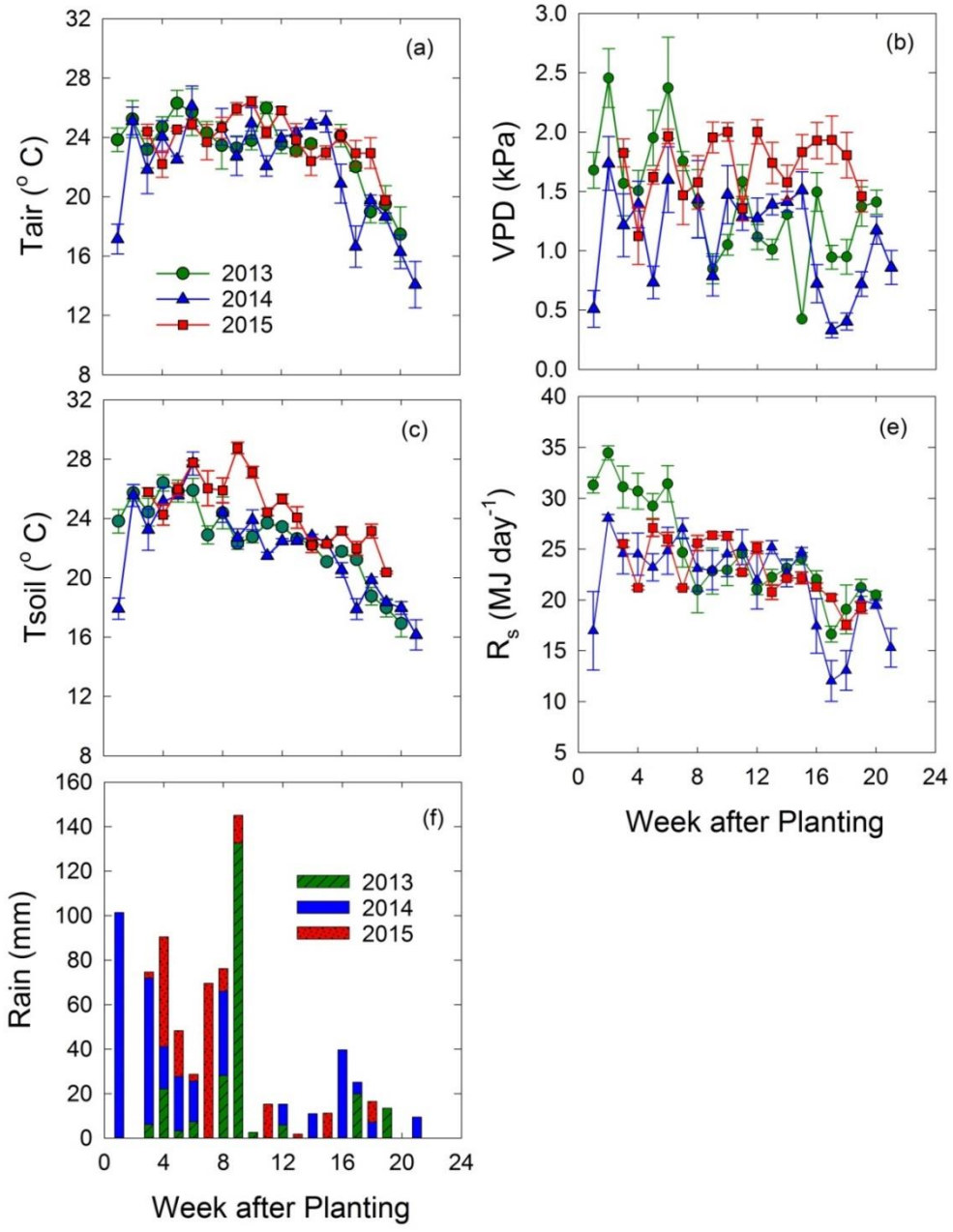


**Figure 2.2. Weekly averages of air temperature (Tair), vapor pressure deficit (VPD), soil temperature (Tsoil), solar irradiance (Rs) and Rainfall. Errors bars represent standard error.**

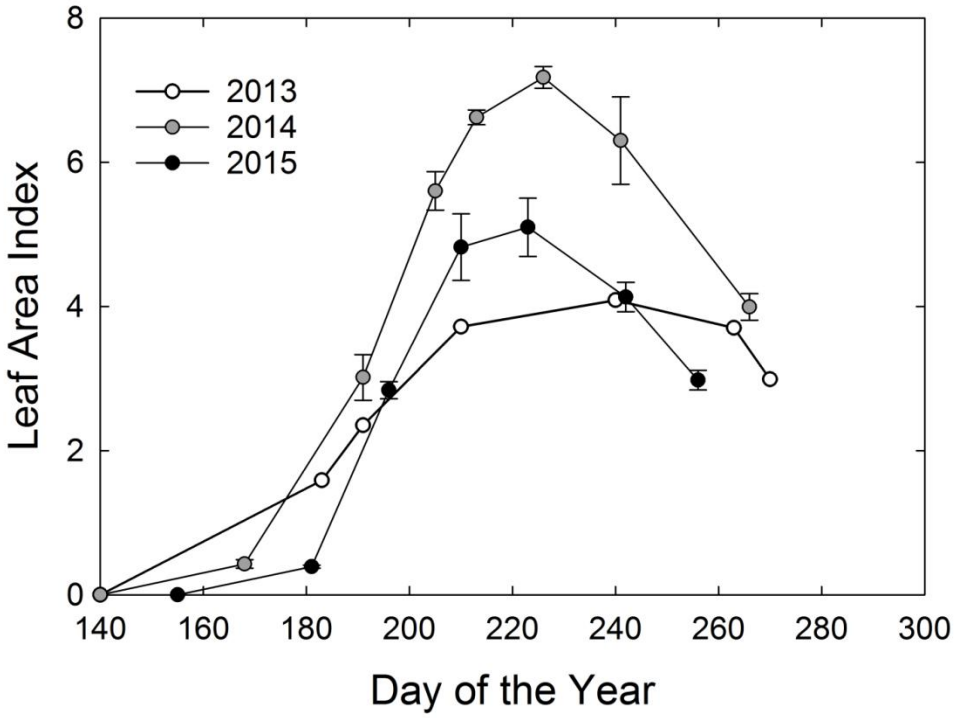


**Figure 2.3. Seasonal evolution of leaf area index (LAI) in sorghum during three growing seasons. Error bars represent standard error of the mean. No replications were conducted in 2013 growing season.**

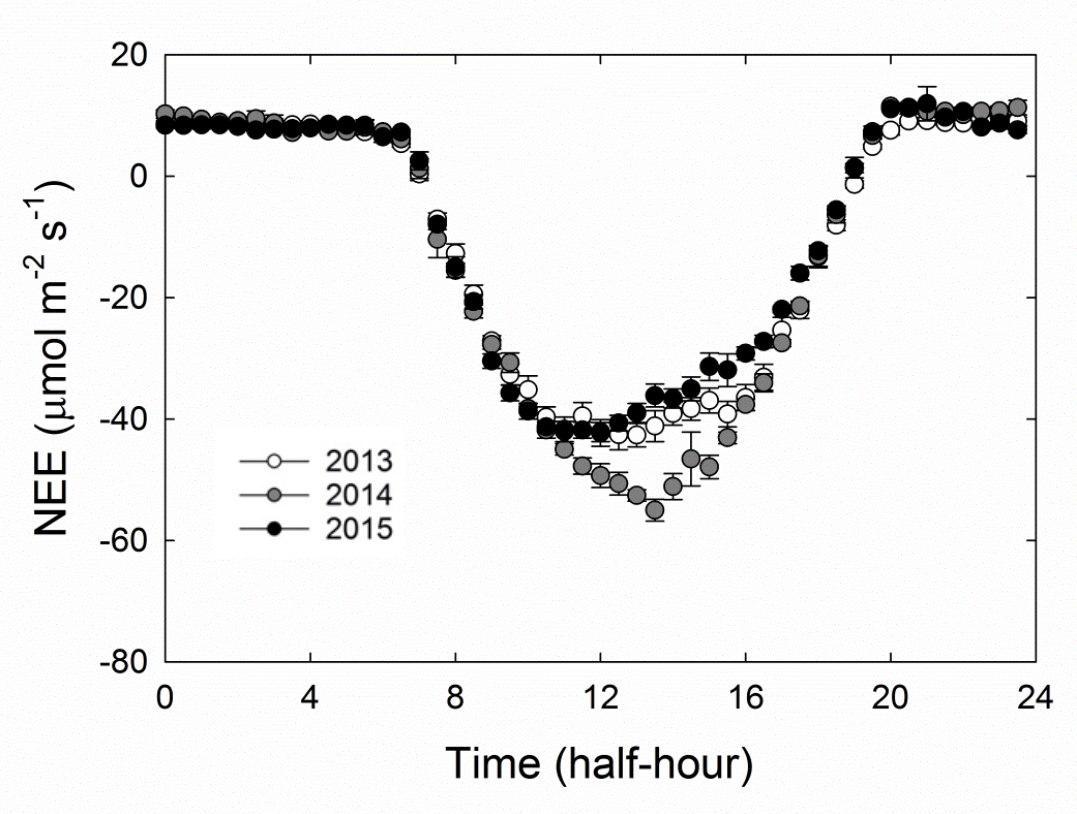


**Figure 2.4. Seasonal evolution of above ground biomass (AGB) over the three growing seasons. Error bars represent standard error. No replications were conducted in 2013.**

**Diurnal Variations: Net Ecosystem Carbon Dioxide Exchange**

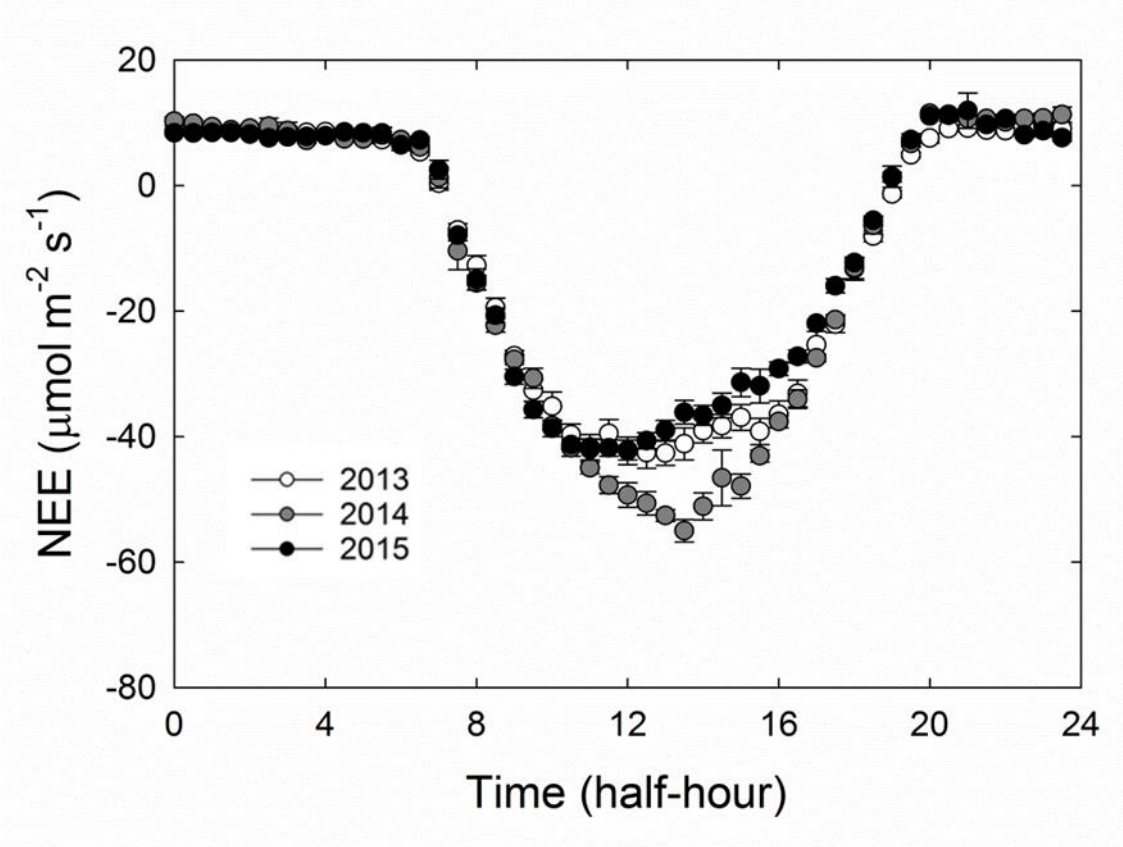


**Figure 2.5. Diurnal patterns of NEE during peak photosynthetic activity period in sorghum. Only clear days with no gap-filled data were selected from the selected period (DOY 201-204 in 2013; DOY 201-209 in 2014; DOY 207-221 in 2015). Error bars represent standard error of mean.**

We compared diurnal variations of NEE at the peak crop growth stage (flag leaf) in all three years by plotting half-hourly values. Figure 2.5 presents the diurnal pattern of NEE during the flag leaf stage in each year. The maximum average half-hourly NEE observed was approximately -55.0 µmoles $m^{-2}$ $s^{-1}$ in 2014, whereas the peak half-hourly NEE was approximately -42.6 µmoles $m^{-2}$ $s^{-1}$ in 2013 and -42.8 µmoles $m^{-2}$ $s^{-1}$ in 2015.

The higher net $CO_2$ uptake in 2014 could be attributed to the higher plant density and LAI that year. Diurnal variations in PAR were similar in all three years. In 2014, net $CO_2$ uptake increased as PAR increased and peaked around solar noon (01:00 p.m.) when PAR was the highest. However in 2013 and 2015, NEE peaked around 10 a.m. and remained relatively constant until 2 p.m., and declined thereafter. The average nighttime loss of $CO_2$ to the atmosphere was slightly higher in 2014 (10.4 µmoles $m^{-2}$ $s^{-1}$) compared to other years (8.6 µmoles $m^{-2}$ $s^{-1}$ in 2013 and 2015). The maximum value of NEE for this sorghum field was higher than that of a non-irrigated biomass sorghum field in Oklahoma (-36 µmoles $m^{-2}$ $s^{-1}$, Wagle et al., 2015). Similar maximum NEE values were reported by Oikawa et al (2015) for an irrigated biomass sorghum field in Arizona.

**Diurnal Variations: Evapotranspiration**

Figure 2.6 shows the average diurnal variations of ET and meteorological variables ($R_n$, $T_{air}$, and VPD) during the peak growth stage in each year. Similar to carbon exchange, higher ET in 2014 could be attributed to high VWC (0.33) and high LAI (7.1) during the peak growth period. Among the climatic variables, there were large differences of VPD across the years during this period. Daytime VPD was the highest in 2015 and lowest in 2013 (Fig. 5C). Average maximum air temperature in 2014 (33.1 $^oC$) and 2015 (33.6 $^oC$) were similar and peaked between 1 and 7 pm (Fig. 5D). In 2013, $T_{air}$ during the same time period was 4 $^oC$ lower (29.6 $^oC$ between 1 and 7 pm). Although the low VPD and air temperature in 2013 could have resulted in low ET that year compared to 2015, the diurnal pattern shows similar ET trends in both years. This could

be the result of high soil moisture conditions in 2013 compared to 2015. Soil VWC measurements confirmed this trend in ET. Average surface soil VWC (5 cm) in 2013 was 0.31 compared to 0.28 in 2015 during the selected peak growth stage days.

Because $R_n$, VPD and $T_{air}$ greatly affect the diurnal changes in ET, half-hourly ET was plotted against respective $R_n$, VPD and $T_{air}$ values (Figure 2.6). The resulting plots show significant distinctive hysteresis patterns in the relationships between ET and the three climatic variables (Figure 2.7). As $R_n$ increased, ET increased and peaked when $R_n$ was the highest during the noon time. ET then declined with decreasing $R_n$ in the afternoon hours. However, higher VPD and air temperature in the afternoon resulted in higher ET in the afternoon than in the morning at the same $R_n$, resulting in an anti-clockwise hysteresis loop. VPD and $T_{air}$ values reached its peak during after noon time and stayed at relatively high values until 7 pm. The stomatal closure response of vegetation to increasing VPD and air temperature in the afternoon hours has been extensively documented by several researchers (Turner et al. 1984; Oikawa et al. 2015; Wagle et al. 2015). Hence, the high VPD and $T_{air}$ values during the day from noon to 7 p.m. are associated with a range of decreasing ET values. Analysis of ET response to meteorological factors at diel scales also revealed significant hysteresis loops in studies conducted by Zheng et al. (2014), Zhang et al. (2014) and Zhou et al. (2014).

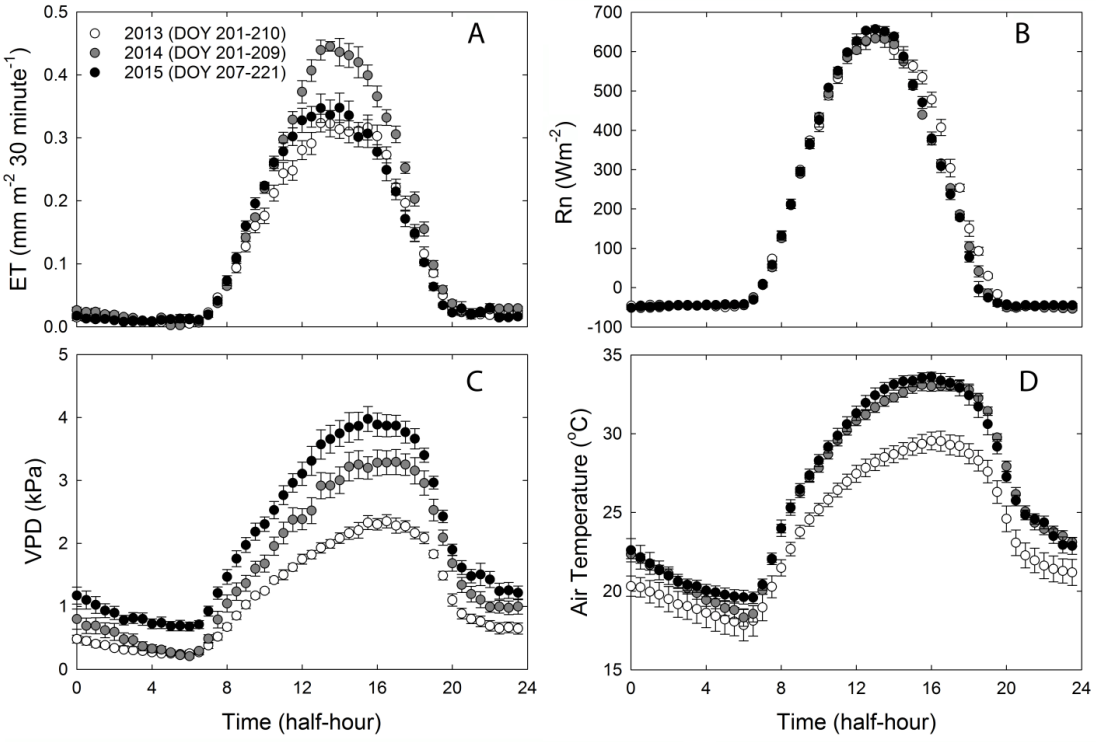


**Figure 2.6. Diurnal trends (a) evapotranspiration (ET), (b) net radiation (Rn), (c) vapor pressure deficit (VPD), and (d) air temperature from a selected period during peak photosynthetic period. The crop was at similar phenological (flag leaf) stage during this period.**

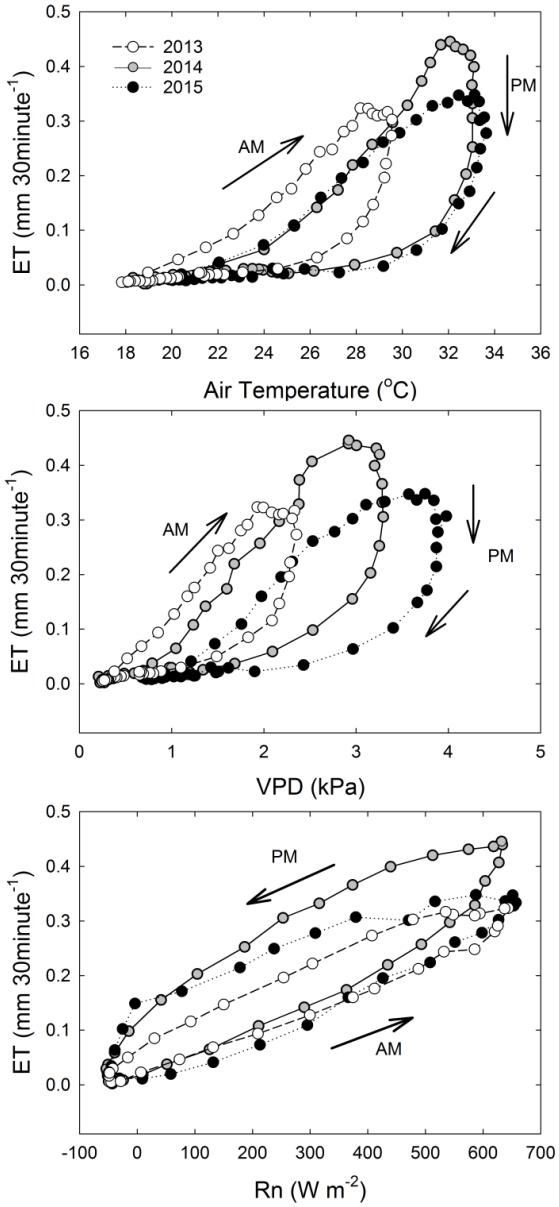


**Figure 2.7. Hysteretic relationship between (from top to bottom) evapotranspiration (ET) and air temperature, ET and vapor pressure deficit (VPD), and ET and net radiation (Rn) during selected period of peak photosynthetic activity period. The crop was at similar phenological stage during this time under optimum soil moisture conditions. Days of the year selected are same as in Figure 2.6.**

**Seasonal Variations in Carbon Exchange**

Thirty minute measurements of NEE and estimations of GPP and $R_{eco}$ were integrated to calculate daily values of these variables (Fig. 2.8a-c). Cumulative estimates of NEE, GPP and $R_{eco}$ are presented in fig. 2.8 (e-f). During all growing seasons, the site was a source of carbon at the beginning and transitioned to a sink later in the season. Carbon uptake peaked in July and August. The maximum daily NEE was -13.3 g C $m^{-2}$ in 2013, -14.5 g C $m^{-2}$ in 2014 and -12.3 g C $m^{-2}$ in 2015. Cumulative NEE during growing season was -710.3 g C $m^{-2}$ in 2013, -665.3 g C $m^{-2}$ in 2014, and -471.0 g C $m^{-2}$ in 2015. In all three years, days with the highest respiration occurred after precipitation or irrigation event. Total $R_{eco}$ includes components of autotrophic respiration and heterotrophic respiration by microorganisms and soil fauna. The intermittent peaks in $R_{eco}$ (Fig. 2.8c) were respiration pulses associated with enhanced microbial activity due to precipitation and irrigation. Cumulative $R_{eco}$ was 872.1 g C $m^{-2}$, 1138.0 g C $m^{-2}$, and 882.2 g C $m^{-2}$ in 2013, 2014 and 2015, respectively.

Longer growing season and greater LAI contributed towards higher C uptake in 2014 than 2013 and 2015. Just like NEE, GPP peaked in July and August across all growing seasons. Maximum daily GPP recorded was -22.8 g C $m^{-2}$ (DOY 203) in 2013 and -26.4 g C $m^{-2}$ (DOY 204) in 2014, and -21.9 g C $m^{-2}$ (DOY 216) in 2015. On the other hand, shorter growing season contributed to lower cumulative GPP in 2015 than 2013, despite having greater LAI. Cumulative seasonal GPP of sorghum was -1591.9 g C $m^{-2}$ in 2013, -1780.9 g C $m^{-2}$ in 2014, an -1353.7 g C $m^{-2}$ in 2015. Canopy development is an important determinant of light interception, hence influences the

primary production and carbon balance (Chen and Black, 1992; Bange et al., 1997; Monteith 1997; Nouvellon et al., 2000; Bréda, 2003; Nagler et al. 2004). As reported by Steiner (1986), increased plant population due to narrow row spacing in sorghum improved light interception and growth. Similarly, Barbieri et al. (2008) reported improved initial growth and light interception in maize when row spacing was reduced. Many studies have indicated greater biomass production following improved light interception as a consequence of reduced row spacing (Andrade et al., 2002; Sharratt and McWilliams, 2005; Drouet and Kiniry, 2008).

We calculated carbon content in the AGB (assuming 50% carbon content in biomass) measured over the growing season. The carbon content of AGB was a strong linear function of the cumulative GPP. Gross primary production is mainly distributed among above ground biomass, below ground biomass and autotrophic respiration (Ise et al., 2010). Combined AGB and below ground biomass constitute net primary production. The slope of AGB and GPP relationship was about 65%, which indicates that 65% of total GPP was allocated to above ground biomass (Fig. 2.9). Apparently, rest of the mass may have been allocated to below ground biomass and autotrophic respiration. Campioli et al. (2015) obtained a similar relationship for managed and unmanaged ecosystems, including forests, grasslands, and croplands. The authors concluded that managed systems favor allocation of more carbon to above ground biomass due to better nutrient influxes. However, our estimates of carbon allocation to AGB are greater (72%) than those reported by Campioli et al. (2015) for managed (about 50%) croplands. Allocation of biomass to different parts could be life strategy for different types of vegetation

(Johnson and Thornley, 1987). For example, Blum and Arkin (1984) reported that sorghum plants growing under water stressed conditions had deep and uniform roots while well irrigated sorghum plants had a high concentration of roots in shallower soil. This suggests that good management of cropping system in terms of nutrients and water in our study may have been responsible for higher biomass allocation to AGB than below ground biomass.

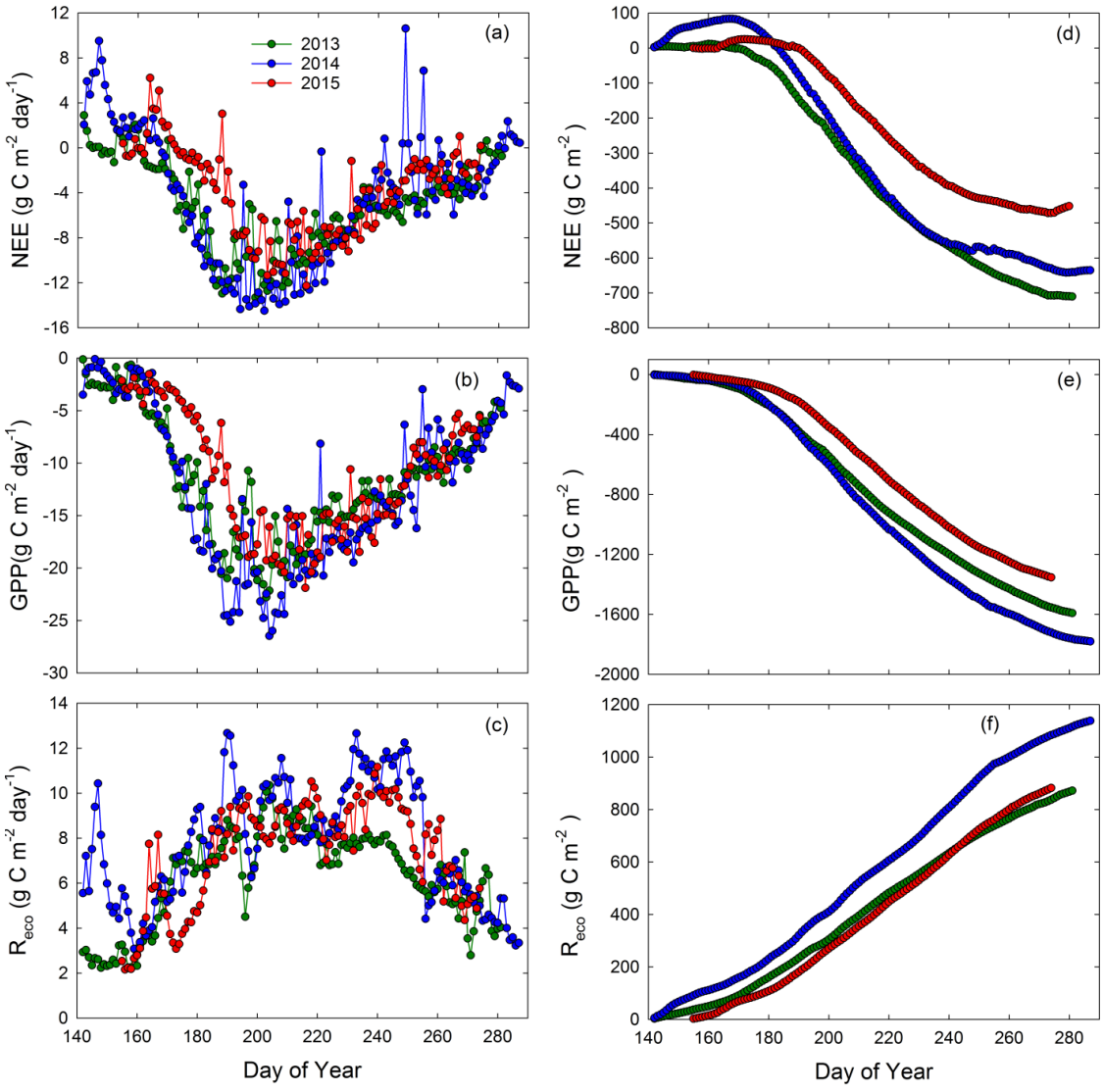


**Figure 2.8. Seasonal courses of daily (sums of) (a) net ecosystem exchange (NEE), (b) gross primary production (GPP) and (c) ecosystem respiration ($R_{eco}$). Seasonal integrals of (d) NEE, (e) GPP, and (f) $R_{eco}$. As per sign convention, negative values indicate carbon uptake and positive sign denotes carbon release to the atmosphere.**

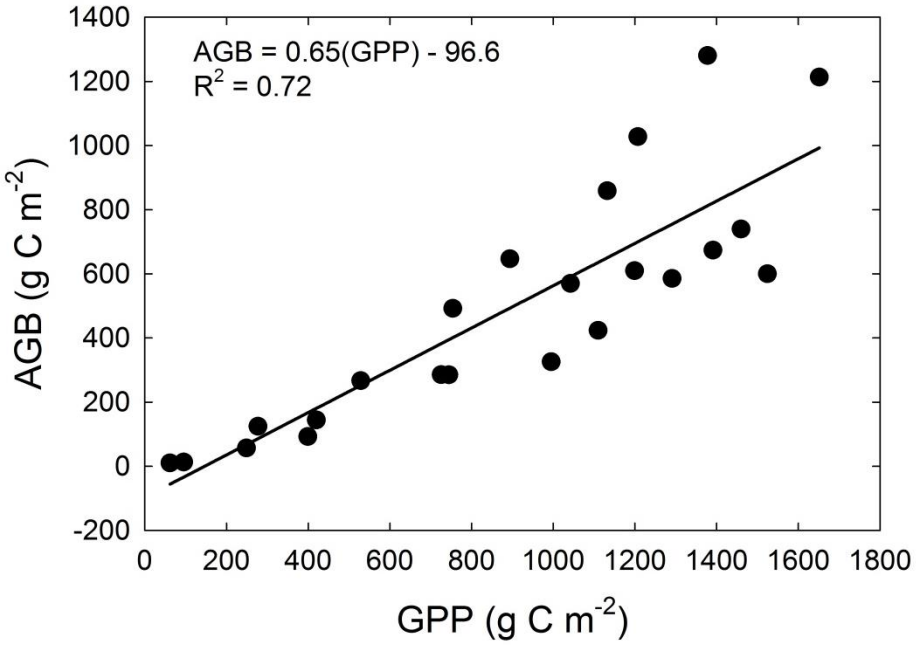


**Figure 2.9. Relationship between carbon content in above ground biomass (g C $m^{-2}$) and cumulative GPP (g C $m^{-2}$).**

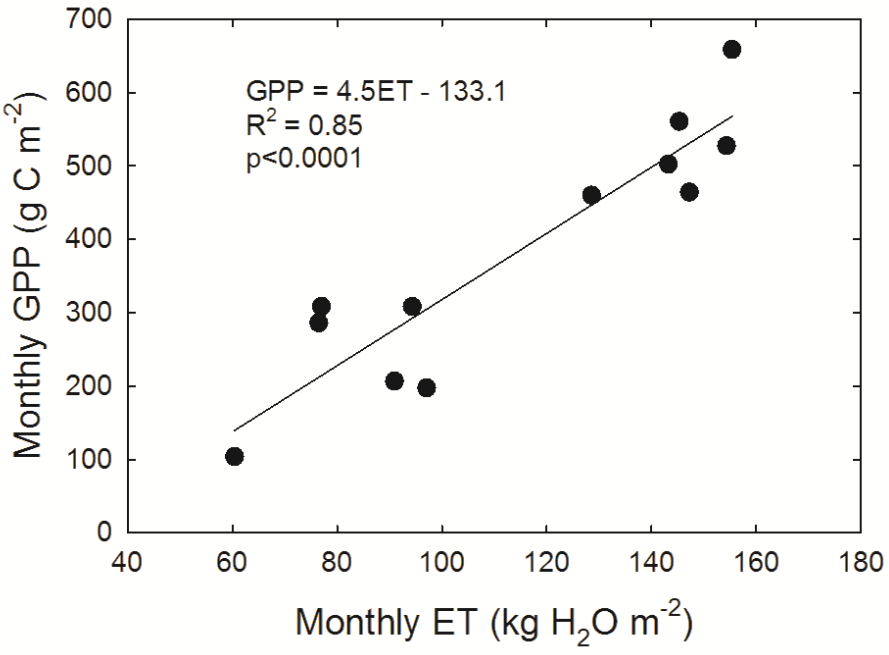


**Figure 2.10. Regression between monthly integrals of (negative) gross primary production (GPP) and evapotranspiration (ET) during active growing season (June-September) across all three year. Coefficient of determination was (0.89).**

**Water Use Efficiency and Evapotranspiration**

Table 2.1 shows cumulative GPP, cumulative ET and WUE calculated for different time periods. During all three years, cumulative ET and GPP for July and August were higher than for other months. Among years, cumulative ET was the lowest in 2015 and the highest in 2014. The higher ET in 2014 was in part the result of higher precipitation received during the growing season (328 mm in 2014 compared to 290 mm in 2013 and 271 mm in 2015). In addition, increased light interception due to narrower spacing in 2014, might have resulted in reduced soil evaporation component (Barbieri et

al. 2012). As such, transpiration component of ET might have increased with more shade and uniform root system due to narrower spacing.

**Table 2.1. Cumulative seasonal gross primary production (GPP), evapotranspiration (ET), and ecosystem water use efficiency (EWUE).**

| Year | GPP (g C m-2) | ET (mm) | WUE (g C $kg^{-1}$ $H_2O$) |
|---|---|---|---|
| 2013 | -1591.9 | 495.4 | -3.2 |
| 2014 | -1780.9 | 522.5 | -3.4 |
| 2015 | -1353.7 | 423.2 | -3.2 |

Monthly WUE was calculated as the ratio of monthly cumulative GPP to monthly cumulative ET. WUE for the three years was the lowest in June, ranging from 1.7 g C $kg^{-1}$ water to 2.3 g C $kg^{-1}$ water. In other months, WUE ranged from 3.0 g C $kg^{-1}$ water to 4.2 g C $kg^{-1}$ water. On average, WUE was the highest in 2014 (3.5 g C $kg^{-1}$ water) and lowest in 2015 (3.0 g C $kg^{-1}$ water). The higher WUE in 2014 might have been due to reduced loss of water through soil evaporation due to narrower row spacing. As mentioned earlier, narrower row spacing also resulted in higher LAI, which increased light interception, resulting in higher GPP. We found a strong linear relationship between monthly GPP and ET (Fig. 2.10). The slope of this linear relationship represents overall ecosystem WUE, which was 4.5 g C $kg^{-1}$ water in our study. The ecosystem WUE estimated in our study was higher than that reported by Wagle et al. (2016) for forage sorghum under rainfed conditions in Oklahoma. These authors reported seasonal WUE of 2.47 g C $kg^{-1}$ water. For other bioenergy crops, Eichelmann et al. (2016)

reported WUE of 3.7 g C $kg^{-1}$ water for rainfed switchgrass in Canada and Wagle et al. (2014) reported 3.2 g C $kg^{-1}$ water for rainfed switchgrass in Oklahoma (Wagle et al. 2014). The higher ecosystem WUE of sorghum in our study is comparable to that of corn (4.1 g C $kg^{-1}$ water) reported by Abraha et al (2016) for the U.S. Midwest. Unlike less intensively managed switchgrass fields, our sorghum field was intensively managed with fertilizer application and irrigation to boost production. Thus, the relatively high ecosystem WUE of forage sorghum at our site is not surprising.

**Bioenergy Production Potential**

Theoretical ethanol yields were calculated using biomass measurements made during the growing season by assuming a conversion rate of 0.30 L ethanol per kg of dry biomass (Oikawa et al., 2015; Chandel et al., 2010). Biomass measured in 2013 before plants entered soft dough stage was 14.6 Mg $ha^{-1}$, which can produce 4,380 L $ha^{-1}$ of ethanol. Since the farmer kept the crop growing for rest of the season to produce seed, the biomass increased to 17.8 Mg $ha^{-1}$ on DOY 264. Estimated theoretical ethanol yield at this stage was 5,340 L $ha^{-1}$. In 2014, the theoretical ethanol yield was 7,682 L $ha^{-1}$ at soft dough stage (Day 241) and 8,906 L $ha^{-1}$ of ethanol at physiological maturity (DOY 267). In 2015, these numbers reduced to 3,420 L $ha^{-1}$ at soft dough stage (Day 242) and 6,980 L $ha^{-1}$ at physiological maturity (DOY 267). In a two year study conducted by Maw et al in central Missouri, average ethanol yield based on a conversion rate of 0.30 L ethanol per kg of dry biomass of high biomass sorghum ranged from 2,010 to 6,270 L $ha^{-1}$.

## CONCLUSION

Seasonal patterns of carbon flux exchanges along with ET and WUE were analyzed for irrigated sorghum in the Southern Great Plains. Phenological and abiotic factors accompanied by length of growing season influenced seasonal carbon uptake properties of sorghum. Narrower row spacing resulted in greater leaf area in 2014. Greater LAI in 2014 resulted in improved light interception and hence considerably higher GPP in that year as compared to 2013 and 2015. Smaller growing season in 2015 resulted in lowest GPP as well as NEE in 2015, despite higher maximum LAI value than 2013. Improved light interception also resulted in greater EWUE in 2014. Overall seasonal NEE and EWUE of irrigated sorghum during all the growing seasons was greater than those reported for rainfed sorghum in the Southern Great Plains region, and matched well with those reported for specific biomass crops at different locations in other studies. These results demonstrate the strong potential of irrigated forage sorghum for production as annual bioenergy crop in the Southern Great Plains. However, the declining water table in the Ogallala aquifer will largely determine the fate of irrigation in the region. Therefore, more investigation is required to quantify the performance of sorghum under irrigated and dryland conditions for future policy and decision making.

# CHAPTER III

# INTER-ANNUAL AND SEASONAL CARBON EXCHANGE DYNAMICS OF A PERENNIAL GRASSLAND COMPARED TO BIOMASS SORGHUM IN THE SOUTHERN GREAT PLAINS

## INTRODUCTION

In addition to meeting the traditional goal of food security , current U.S. agriculture is facing an unprecedented challenge in securing America's energy future. The Renewable Fuels Standard Program (RFS2) has projected a requirement of 36 billion gallons (BG) of renewable fuel to be blended into transportation fuel by 2022, an increase of 27 BG compared to the 9 billion gallon target established in 2008 (USDA, 2010; RFA 2016). Despite lower crude oil prices in recent times, a record ethanol production of about 23 BG was registered in the U. S. in 2016 (RFA, 2017). Out of the 23 BG, the share of advanced second generation, biomass based biofuels (50% or more lifecycle greenhouse gas reduction) was only about 5.7 BG. To bridge this gap, an increase in the production of second generation bioenergy crops is anticipated in future. Large scale production of bioenergy crops is expected to have significant implications on local as well regional environment. However, environmental impacts of large scale production of bioenergy crops have not been addressed adequately (Berndes, 2002; Robertson et al., 2008; Rowe, 2009; Wagle et al., 2015). Therefore, it is important to assess the potential environmental impacts of large scale production of bioenergy crops.

Second generation biofuels can be produced from annual crops or perennial crops. Compared to annual crops, perennial crops have relatively lower agronomic management requirements (such as tillage), lower nutrient requirements, greater energy production, and reduced greenhouse gas emissions (GHG) (Adler et al., 2007; Parrish and Fike, 2005; Heaton, et al., 2004). Perennial grasslands with generally high root to shoot ratio can add significantly to below ground carbon storage (Jackson et al., 1997). However, perennial grasses such as *miscanthus* and switchgrass (*Panicum virgatum* L.) can take a number of years to establish a significant crop stand for lucrative biofuel production (Propheter et al., 2010). Several researchers have reported annual crops performing comparable to or better than perennial crops in productive and marginal environmental conditions, mainly due to lower yields of perennial grasses during the initial establishment years (Hallam et al., 2001; Boehmel et al., 2008; Propheter et al., 2010; Zenone et al., 2013). In addition, annual crops provide flexibility of crop rotation to farmers (Carpita and McCann, 2008; Cotton et al., 2013). Such factors associated with perennial and annual bioenergy crops are critical for producers' acceptance of these bioenergy crops.

Sorghum (*Sorghum bicolor* L.) is a drought tolerant annual crop with potential to establish itself as a major annual bioenergy crop especially in semi-arid areas (Rooney, 2007). Sorghum production is cheaper than corn production due to its drought tolerant properties, lower requirement of fertilizers and efficient use of nitrogen, phosphorus and potassium (Rooney, 2007; Shoemaker and Bransby, 2010). In addition, sorghum production has shown to restore soil organic matter in several studies depending upon

tillage practices and amount of biomass left on soil surface (Halvin et al., 1990; Polley, 1992; Cotton et al. 2013b; Meki et al, 2013;). Improved sorghum cultivars with brown midrib (*bmr*) mutation have lesser extent of lignin content in cell wall than conventional forage sorghum. Hence *bmr* cultivars of sorghum have better conversion efficiency of lignocellulose to ethanol (Bucholtz et al., 1980; Cherney et al., 1991; Saballos et al, 2008; Corredor, 2009; Dein et al., 2009). Sorghum is an established cropping system throughout the world including the U. S. for grain as well as forage production. Therefore, sorghum with its already established cropping systems and physiological advantage over corn, has the potential to emerge as a major annual bioenergy crop.

Perennial grasses such as switchgrass and *miscanthus* are becoming popular as major bioenergy crops in North america and Europe. While the popularity of specific perennial biomass crops such as switchgrass and *miscanthus* as bioenergy crops has peaked recently (McLaughlin et al., 1999; Lewandowski et al., 2003), the perennial grasslands had been considered as potential bioenergy sources since 1980s, especially in Europe and North America (McLaughlin et al., 2002; Lewandowski et al., 2003; Prochow et al., 2009). *Bothriochloa bladhii* also known as old world bluestem (OWB) is a C4 perennial bunch grass, native to India that had been introduced successfully in the Southern Great Plains in 1990s (Rajan et al., 2015). Many cultivars of *Bothriochloa spp.* with different physiological and growing properties had been successfully introduced as pastures in the Southern Great Plains. Old world bluestem has been shown to respond positively to N fertilization and irrigation (Berg, 1990; Berg and Sims, 1995; Buttrey et al. 2011). Buttrey et al. (2011) compared six perennial grasses (for multiple clippings)

including switchgrass and OWB (WW Spar) under irrigated and dryland conditions. The authors reported OWB to be the best overall grass in terms of dry matter yield, forage quality and water use efficiency (WUE). Griffith et al. (2010) demonstrated the dominance of the OWB in a mixed-prairie where OWB cover increased from 73 to 96% within three years of planting. Old World Bluestem is one of the dominating grasses grown on the conservation reserve program (CRP) lands in the Southern Great Plains (Li et al., 2017). These CRP lands can well serve as sources of biofuel feedstock. As such, bringing these lands to production will eliminate the cost government incurs to refrain producers from cultivating these lands. Old World Bluestem has many desirable characteristics as a biofuel crop, such as wide range of adaptation and high biomass productivity (Grabowski et al., 2000).

Environmental sustainability is important for large scale production of bioenergy cropping systems. Carbon exchange and energy balance of a system can indicate the overall environmental sustainability of a cropping system (Zenone et al., 2013). Therefore, the objective of this study was to assess and compare seasonal and inter-annual variation of net ecosystem exchange (NEE) of carbon dioxide ($CO_2$), ecosystem respiration ($R_{eco}$) and gross primary production (GPP) of high biomass forage sorghum and OWB in the Souhtern Great Plains. Both cropping systems were managed by producers, therefore this provided us an opportunity to collect data under standard managements practices followed in the region. Environmental variables driving these flux exchanges were also assessed in this study.

Eddy covariance method is the most popular method for studying the C cycle of different ecosystems (Baldocchi et al., 2001; Baldocchi, 2003). Using this method, the carbon dioxide ($CO_2$) flux is determined as the covariance between vertical wind velocity and $CO_2$ concentration which are measured using fast-response instruments (Goulden et al., 1996; Ham and Heilman, 2003). The net ecosystem exchange (NEE) measured using the eddy covariance represents the balance between C uptake and release. The carbon flux exchanges in the two selected fields crops were measured using the eddy covariance method. Carbon exchange dynamics of sorghum and OWB have been rarely addressed using eddy covariance systems, especially in the Southern Great Plains. It is important to study and assess the physiological behavior of these crops as different biomes have different physiological responses to environmental variables. Eddy covariance data will be useful in validating land surface and remote sensing models to extrapolate carbon balance of the agroecosystems to different temporal and spatial scales (Xu and Baldocchi, 2004). More importantly, environmental sustainability of annual and perennial bioenergy crops will be critical for decision and policy making agencies before proceeding with large scale production of these crops (Berndes, 2002; Robertson et al., 2008; Fargione et al., 2008; Rowe, 2009; Zenone et al., 2013)

## MATERIALS AND METHODS

### Study Site

This study was conducted in two different farmers' fields fitted with a center pivot irrigation systems in the Texas High Plains region. The high biomass forage sorghum field, managed for commercial seed production, was located approximately 4.5

km northeast of Plainview, TX (34°12’34.70’’ N and 101°37’50.85’’ W, 1100 m elevation). The cultivar planted was Surpass XL *bmr*. Sorghum was planted on one half of the field and the remaining half was planted with cotton (*Gossypium hirsutum* L.). The farmer practiced crop rotation between these crops on both halves of the field. Management practices prior to planting sorghum included mowing of cotton stalk after harvesting previous cotton crop followed by tillage in spring and before planting the crop. Total area planted with sorghum each time was about 25 ha. The crop was planted on 20 May in 2013 and 2014 at a seeding rate of 4.5 lbs $acre^{-1}$. Heavy rains in late May during 2015 delayed planting, thus the crop was planted on June 4 in 2015 at the same seeding rate. The row spacing in 2013 and 2015 was 1 m and 0.5 m inches in 2014. Urea was broadcasted in the field in spring before planting at a rate of 150 kg N $ha^{-1}$. In addition, 30 kg $P_2O_5$ $ha^{-1}$ was also applied prior to planting. The field was irrigated with low elevation application center-pivot irrigation system during the crop growth period. For first 40 days the field was supplied with 19 mm and for rest of the season it was supplied with 38 mm inch water during each irrigation event. The field was supplied with about 400 mm of water through irrigation in 2013 and 2014 each, and about 270 mm in 2015. Also, the field was cultivated between the plant rows to kill weeds twice in June every year when the crop was still small. The field was harvested for seed on 8 October in 2013, on 14 October in 2014, and on October 1 in 2015. The growing season was 140, 147, and 119 days long for 2013, 2014, and 2015, respectively. Equipment availability and late season rainfall affected the timings of harvest. The field remained fallow post-harvest in winter and spring. The remaining stalk was grazed by cattle in

March 2014 and in January 2015. A fence was put around the tower while the cattle were present in the field. Since the crop was grown in rotation with cotton, the new crop was planted on other half of the field where cotton was produced in previous season. The major soil mapping unit at the study site is Pullman clay loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with 0 to 1% slope.

The perennial grassland was located about 5 km ($34^{o}$ 08'47" N, $101^{o}$25'48" W) west of Lockney, TX and was established in 2007. The pasture was seeded with WW-B Dahl Old World Bluestem (OWB) (*Bothriochloa bladhii* L.) at the seeding rate of 2.8 Kg seed $ha^{-1}$. "WW-B. Dahl" OWB was released in 1994 jointly by USDA-ARS, USDA-SCS, Texas Tech University, and the Texas Agricultural Experiment Station originally from a selection made in India (Rogers et al., 2012). It is a bunchgrass with an upright growth habit and has better drought tolerance and water use efficiency than conventional cropping systems in the Southern Great Plains (Allen et al., 2005). Total area of the site was about 42 ha. Until 2011, the field was used for grazing by the cattle or for seed production. Although, this field was equipped with a center pivot irrigation system, no irrigation was supplied during the study period (2013-2015). Moreover, no nutrients were supplied and the field was never grazed during the period of study. The growing season for the crop roughly ranged from May to October. Peak growing season occurred from June to July depending upon precipitation. The grass remained in vegetative state for the most part of the growing season and bloomed in late September/early October. The field was harvested for seed on November 14, 2014. No

seed harvesting was done in 2013 and 2015. The field was never harvested for hay. Major soil mapping unit in the field was Pullman clay loam with 0-1% slope.

**Eddy Covariance Data Collection**

Carbon dioxide, water vapor/latent heat (LE) and sensible heat (H) fluxes were measured in the fields using eddy covariance systems. While the eddy covariance system in grassland was established in 2010, the tower in sorghum was established at planting in 2013. Both towers were set up in the middle of the fields, with a fetch of about 150 m from all directions. An integrated sonic anemometer (Model CSAT-3A, Campbell Scientific) and infra-red gas analyzer (IRGA, Model EC-150, Campbell Scientific) called the IRGASON was used to measure wind velocity and $CO_2$, $H_2O$ vapor concentration, and H in the ambient atmosphere. In the grassland, the $CO_2$, $H_2O$ vapor concentration was measured using a LI-7500 IRGA (LI-COR Biosciences) and wind velocity and sensible heat flux were measured using sonic anemometer (Model CSAT-3A, Campbell Scientific). These instruments were set up facing south-southwest (in the prevailing wind direction) at a height of about 2.1 m from ground surface. The height of the instrument was adjusted in sorghum field during growing season with increasing crop height to a final height of about 2.6 m from ground. Other environmental variables measured at both sites included air temperature ($T_{air}$) and relative humidity (RH) (HMP50, Campbell Scientific), net radiation (Kipp & Zonen NR-Lite net radiometer), photosynthetically active radiation (PAR) (LI-200SL quantum sensor, LI-COR), solar irradiance (LI-190SB pyranometer, LI-COR), precipitation (TE525 rain gauge, Campbell Scientific), soil temperature ($T_{soil}$) at 4 cm below the surface (TCAV

averaging soil thermocouples, Campbell Scientific), and soil volumetric water content at 4 cm below the surface (CS-616 water content reflectometer, Campbell Scientific). Self-calibrating soil heat flux plates (HFPSC-01, Hukseflux, Campbell Scientific, Logan, UT) were used to measure soil heat flux at 8 cm depth from soil surface. Soil heat storage which is the amount of heat stored in 8 cm soil depth over soil heat flux plates was calculated using the following equation:

$$S = \frac{\Delta T_s C_s d}{t} \qquad [3.1]$$

Where S is the storage term, $\Delta T_s$ is change in surface soil temperature, *d* is depth of soil in meters above soil heat flux plate, $C_s$ is the heat capacity of moist soil, and *t* is time in seconds. Heat capacity of soil can be calculated from following equation using bulk density ($\rho_b = 1.3$ gm $cm^{-3}$), volumetric water content ($\theta_v$), density of water ($\rho_w = 1000\ kg\ m^{-3}$), heat capacity of water ($C_w = 4.2\ kJ\ kg^{-1}K^{-1}$), and heat capacity of dry soil ($C_d = 840\ J\ kg^{-1}K^{-1}$):

$$C_s = \rho_b C_d + \theta_v \rho_w C_w \qquad [3.2]$$

Soil heat storage term was calculated using temporal variations in soil temperature and soil moisture in Eq. [3.1] and [3.2]. Soil heat storage term and measured soil heat flux were added to obtain soil heat flux at surface (G).

Infra-red gas analyzer and net radiometer surfaces were cleaned regularly as per the manufacturers' guidelines to avoid accumulation of dust. Data from the CSAT3A sonic anemometer and IRGA system were measured at 10-Hz sampling rate using a CR3000 datalogger (Campbell Scientific). All other environmental variables were

measured at 5 seconds interval. The datalogger was programmed to calculate and save 30-min average values of all environmental variables. The raw 10-Hz wind velocity and EC150/LI-7500 data were saved for further post-processing and analysis of $CO_2$ and energy fluxes.

**Data Processing and Gap filling**

Data from eddy covariance system was used to calculate half-hourly $CO_2$ and energy fluxes. The flux measured from the eddy covariance tower is the average of the product of the covariance between scalar ($CO_2$, water vapor and temperature) and vector (vertical motions of wind). The high frequency data were analyzed using EddyPro 4.0 software (LI-COR Biosciences, Lincoln, NE). Flux computation requires a series of operations in order to apply corrections to raw data for flux computation. Some of these corrections include spike removal, block averaging, coordinate rotation, spectral corrections for flux losses (Moncrieff et al., 1997), and correction for air density fluctuations (Webb et al., 1980). EddyPro software has built-in functions to apply these corrections and process the eddy covariance data.

Occasional gaps in the flux data occurred during power failure or maintenance and they were gap filled. In addition, the physically implausible values in the data were also filtered and gap filled. Further, the flux is usually underestimated during low turbulence conditions and therefore, data during low turbulence conditions (when the friction velocity (u*) was <0.10 m $s^{-1}$ (Rajan et al., 2015)) was filtered and gap-filled. In sorghum, the average u* during growing season was 0.31 $ms^{-1}$, 0.33 $ms^{-1}$, and 0.31 $ms^{-1}$ in 2013, 2014, and 2015, respectively. The average u* during growing season in

grassland was 0.31 m $s^{-1}$, 0.36 m $s^{-1}$, 0.31 m $s^{-1}$ in OWB. After screening the data for out of the range and above mentioned filtering criteria, the amount of data which was either missing or did not meet the quality check criteria was about 21%, 8%, and 40% in 2013, 2014, and 2015, respectively. During the growing season, 21%, 13% and 3% data was gap-filled in 2013, 2014, and 2015 respectively. The amount of data to be gap filled in grassland was 32, 16 and 25% of the total data in 2013, 2014, and 2015, respectively.

The CarboEurope and Fluxnet eddy covariance gap-filling on-line tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/) was used for gap filling, which is based on the methods similar to those described in Falge et al. (2001) and Reichstein et al. (2005). The data of direct interest such as fluxes is gap filled by averages of ± 7 days windows under similar meteorological conditions when all the meteorological variables are available. The similarity of meteorological conditions is defined when radiation, $T_{air}$ and VPD do not fluctuate beyond threshold values of ±50 W $m^{-2}$, ±2.5 $^{o}$C, and ±0.5 kPa, respectively. This window is expanded to ±14 days, in case similarity in meteorological conditions is not achieved within 7 days window.

Flux partitioning into GPP and $R_{eco}$ were done using empirical model developed from night-time NEE and soil temperature (4 cm) data. Night-time NEE values represent $R_{eco}$, which includes soil and plant respiration. Night time was selected when the global radiation was below 20 W $m^{-2}$ threshold. Daytime $R_{eco}$ was evaluated using an exponential regression model developed between nighttime NEE measurements and corresponding soil temperature ($T_{soil}$) measurements made at the 4-cm depth. The general form of the regression model is:

$$R_{eco} = Ae^{(B*Tsoil)} \qquad [3.3]$$

where A and B are constants evaluated with least squares regression.

Only original measured data was used to parametrize this model. Further, daily $R_{eco}$ and NEE was calculated by integrating daytime and nighttime measurements. Daily gross primary production (GPP) was calculated as:

$$GPP = R_{eco} - NEE \quad [3.4]$$

Ecosystem respiration includes both heterotrophic and autotrophic respiration. The sign convention used was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

**Energy Balance Closure**

Quality of eddy covariance data is very important and can be determined by the energy balance closure (Wilson et al., 2002). The energy balance closure at the site was examined by regressing 30-min $R_n$ data against the corresponding sum of LE, H, and G. To examine energy balance closure a linear regression was performed between available energy (Rn-G), and energy fluxes of LE and H. While soil heat storage term was calculated as mentioned above, the canopy storage and energy used for photosynthesis was not calculated for this analysis. Good quality original data for LE and H were used to assess energy balance closure when all the energy balance components were available. Physical and biochemical energy storage terms in the crop canopy layer were assumed to be negligible and thus, were not used in the energy balance closure (Wilson et al., 2002).

The difference between $R_n$ and G represents the available energy at the surface. Assuming negligible heat storage within the canopy and net horizontal advection of energy, the energy balance can be described as:

$$R_n - G = LE + H \qquad [3.5]$$

The sign convention used for Rn and G are positive when the flux is downwards and negative when the flux is upward. The sign convention used for LE, H and C fluxes was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

**Light Response Curves**

Light response curves were obtained by obtaining the relationship between daytime NEE with photosynthetic photon flux density (PPFD). Daytime was differentiated from night when photosynthetic photon flux density (PPFD) was >1 μmol photon $m^{-2}$ $s^{-1}$. To understand the photosynthetic response of the sorghum crop at different growth stages, a rectangular hyperbola model was used (Flanagan et al., 2002; Hussain et al., 2011).

$$GPP = \frac{GPP_{max} PAR}{PAR + \left(\frac{1}{\alpha}\right) GPP_{max}} + R \qquad [3.6]$$

where $NEE_{max}$ is the maximum NEE rate (μmol $CO_2$ $m^{-2}$ $s^{-1}$), PAR is the photosynthetic active radiation (μmol photon $m^{-2}$ $s^{-1}$), α is the initial slope of the light response curve (μmol $CO_2$ $m^{-2}$ $s^{-1}$/μmol photon $m^{-2}$ $s^{-1}$), $GPP_{max}/\alpha$ is the PAR associated with half of the maximum GPP rate, and R is the intercept term, which is the average daytime $R_{eco}$

(μmol $CO_2$ $m^{-2}$ $s^{-1}$). In the present study, we evaluated Eq. [3.6] at PAR of 2000 μmol photon $m^{-2}$ $s^{-1}$, and the term $(NEE_{max} + R)_{2000}$ represents the average maximum uptake rate.

**Plant Data**

Plant dry biomass weight was measured during the growing season. Sorghum plant samples were taken randomly (3 replications) from the field to measure leaf area index (LAI), dry leaf mass and dry shoot mass. For grasslands, four random plant samples (for green, yellow leaves and litter) were taken from 0.25 $m^2$ area. No LAI measurements were conducted on the grass samples. Plants were stored in an ice chest in the field and leaf area of sorghum was measured (after separating leaves from shoots) using a leaf area meter (Model LI-3100, Licor Biosciences, Lincoln, NE) immediately after they were brought to the laboratory. For grass samples, green and yellow leaves were separated after samples were brought to the lab. After measuring leaf area, leaves and shoots were stored in paper bags and dried at 65$^{o}$C for one week. Dry mass of shoot and leaves was taken immediately after removing the dried samples from the oven. Plant density (number of plants per $m^2$) and leaf area were used to calculate the LAI.

## RESULTS

### Weather

With the fields separated by roughly 15 km, precipitation events occurred in both fields, with more-or-less in temporal synchrony with slight difference in magnitude (Fig. 3.1). Long term (2002-2010) average annual precipitation recorded by local mesonet station in Plainview is 470 mm. Years 2011 and 2012 were exceptionally dry and thus were excluded from the long term average calculation. During the study period both fields received about 10, 15 and 80% more precipitation than the long-term average in 2013, 2014 and 2015, respectively. Years 2013 and 2015 received fewer precipitation events during the non-growing season, while year 2014 remained relatively dry during this time. May 2013 remained dry, while the corresponding time in 2014 and 2015 received considerable amount of rainfall. In 2013, first significant precipitation event came in June. Most of the precipitation received in 2015 was received till first week of July. Month of August was comparatively drier in 2014 and 2015 than in 2013. An extended dry period was observed in 2015 from mid-July to late September.

**Table 3.1: Monthly average maximum (Tmax) and minimum (Tmin) air temperature values in (a) old world bluestem and (b) sorghum field for year 2013, 2014 and 2015.**

(a)

| Month | 2013 | | 2014 | | 2015 | |
|---|---|---|---|---|---|---|
| | Tmax | Tmin | Tmax | Tmin | Tmax | Tmin |
| | Degree C | | Degree C | | Degree C | |
| January | 11.7 | -2.6 | 12.7 | -7.1 | 9.1 | -3.5 |
| February | 12.4 | -3.3 | 12.1 | -4.6 | 13.6 | -3.3 |
| March | 19.4 | 0.75 | 18.4 | -1.3 | 19.2 | 1.0 |
| April | 22.9 | 3.5 | 23.4 | 5.3 | 23.6 | 7.2 |
| May | 28.4 | 10.6 | 28.2 | 10.8 | 23.9 | 11.3 |
| June | 32.6 | 18 | 30.9 | 17.4 | 30.0 | 17.5 |
| July | 31.5 | 18.4 | 30.3 | 17.8 | 31.9 | 19.1 |
| August | 32.8 | 18.2 | 33.5 | 17.3 | 32.6 | 17.4 |
| September | 30.2 | 14.7 | 25.9 | 15.4 | 31.0 | 16 |
| October | 23.7 | 6.7 | 24.4 | 7.5 | 23.6 | 9.6 |
| November | 15.2 | 0.5 | 14.8 | -1.3 | 17.0 | 1.9 |
| December | 10.1 | -5.3 | 10.9 | -1.0 | 15.5 | -1.0 |

(b)

| Month | 2013 | | 2014 | | 2015 | |
|---|---|---|---|---|---|---|
| | Tmax | Tmin | Tmax | Tmin | Tmax | Tmin |
| | Degree C | | Degree C | | Degree C | |
| January | | | 12 | -6.5 | 9 | -3.5 |
| February | | | 11.9 | -4.4 | 13.3 | -3.1 |
| March | | | 17.9 | -1.4 | 18.6 | 1.4 |
| April | | | 22.7 | 5.0 | 23 | 7.2 |
| May | | | 27.1 | 10.9 | 23 | 11.6 |
| June | 32.1 | 18.1 | 30.9 | 17.4 | 30.3 | 17.9 |
| July | 29.8 | 17.2 | 29.9 | 17.9 | 31.5 | 19.1 |
| August | 31.3 | 17.2 | 31.8 | 16.6 | 31.3 | 17.2 |
| September | 29.1 | 14.2 | 26 | 15 | 30 | 15.6 |
| October | 22.7 | 6.8 | 24.5 | 7.2 | 23.2 | 9.7 |
| November | 14.8 | 0.7 | 14.8 | -1.6 | 16.9 | 1.7 |
| December | 10.2 | -5.5 | 11.5 | -2.2 | 15.1 | -0.1 |

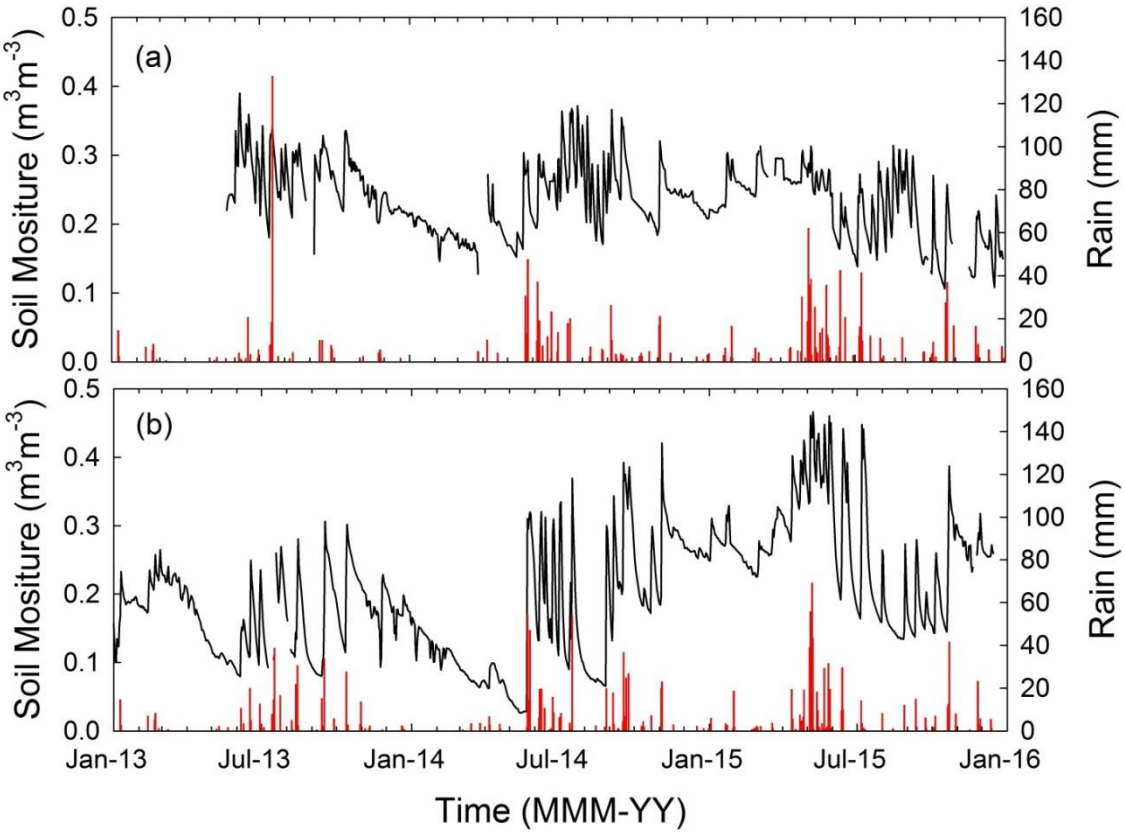


**Figure 3.1. Surface soil moisture (volumetric water content in $m^3$ $m^{-3}$) presented by line plot and precipitation presented by red bars in (a) sorghum field at 5 cm and (b) old world bluestem at 5 cm.**

Soil moisture was sensitive to precipitation timings and magnitude in OWB field (Fig. 3.1). In OWB, average surface volumetric water content (VWC) at 5 cm depth, during growing season (May-October) was 0.15 in 2013, 0.18 in 2014, and 0.25 in 2015. The driest months of the season in OWB were May (VWC 0.10) in 2013, August (VWC 0.10) in 2014, and September in 2015 (VWC 0.17). On the other hand, dry conditions hardly prevailed in sorghum during the growing season as it was irrigated regularly.

Average surface VWC (5 cm) during active growing season (June-September) was 0.27 in 2013, 0.24 in 2014, and 0.21 in 2015. Soil VWC declined once the irrigation was stopped by second week of September in sorghum field, though late season rainfalls in 2013 and 2014 replenished the soil moisture in late September.

Table 3.1a, and b show the mean monthly maximum and minimum temperature in OWB and sorghum fields along with 30 year monthly averages. Monthly averages maximum temperature and minimum temperature were within ±0.5 $^{o}$C to the 30 year averages (1981-2010), except in September 2014 and May 2015 (accessed from http://www.usclimatedata.com/climate/plainview/texas/united-states/ustx1059/2017/1). Average maximum temperature in September 2014 and May 2015 was about 2.1$^{o}$C and 1 $^{o}$C lower than 30 year mean. Both fields showed a dip in maximum temperature during these months due to cold fronts and rainfall that took place during these months. Average annual temperature recorded for two complete years in sorghum was 13.8 $^{o}$C and 14.8 $^{o}$C in 2014 and 2015, respectively. Average annual temperature recorded at the OWB field was 14.4, 14.0, and 15.0 in 2013, 2014, and 2015, respectively. The recorded annual average temperatures were close to the mean annual 30 year (1981 – 2010) average temperature (15.0 $^{o}$C) recorded in Hale and Floydada county (obtained from http://www.usclimatedata.com/climate) in 2013 and 2015.

**Energy Balance**

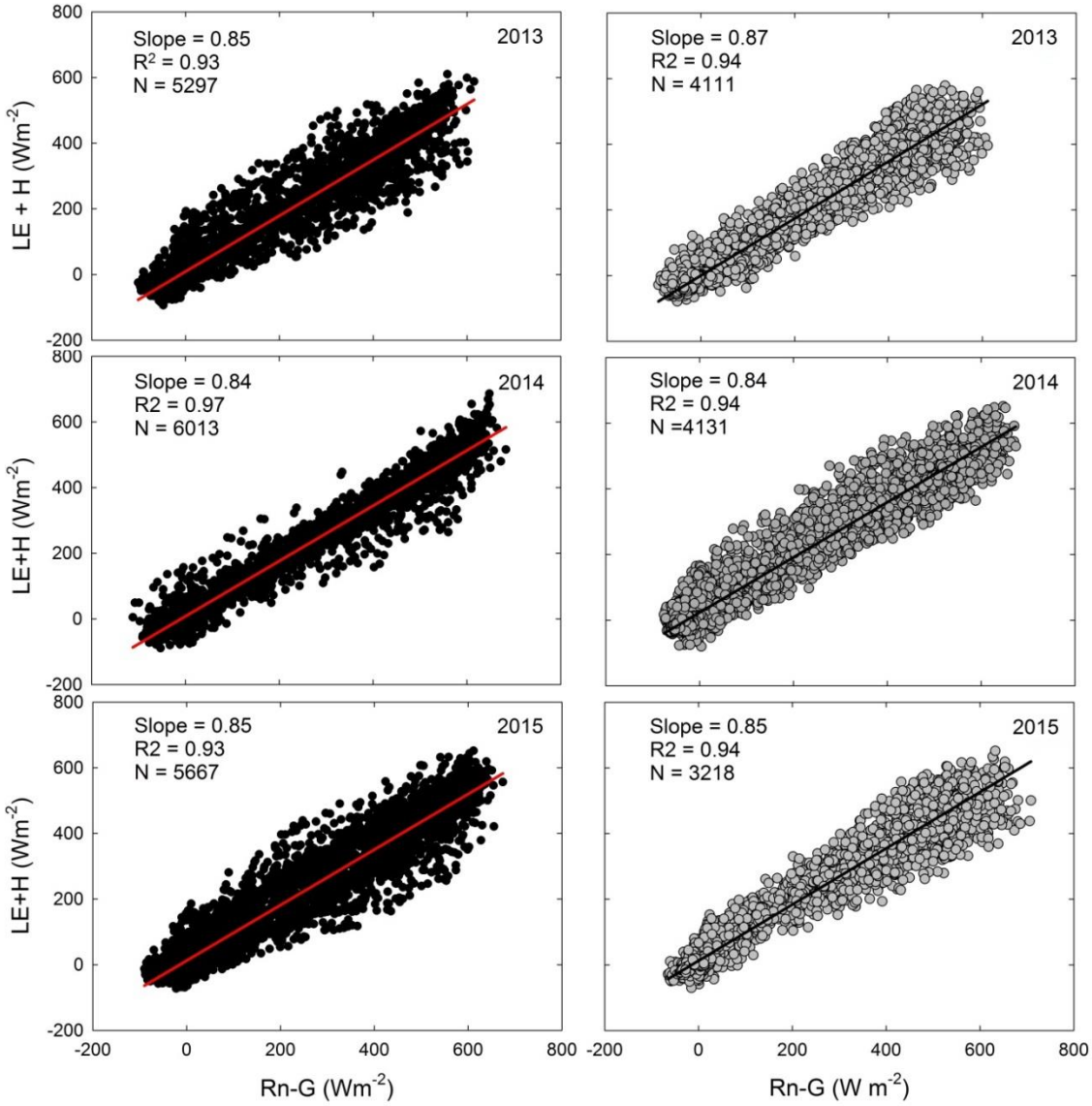


**Figure 3.2: Energy balance closure during growing season in old world bluestem (black circles) and sorghum (grey circles). Only original data (no gap filled) was used when all the variables were available. All linear relationships were significant ($p<0.0001$).**

Energy balance closure is an important assessment of the quality of eddy covariance data (Wilson et al., 2002; Foken et al., 2008). Growing season data was used to obtain energy balance closure. Figure 3.2 shows energy balance of the both crops during each growing season. Energy balance closure was similar among both crops, ranging from 84% to 87% (with coefficient of regression ($r^2$) more than 0.90 during all years of study). These energy balance closure values fall within the range (70-90%) generally reported for croplands (Stoy et al. 2013). Lack of energy balance closure can result from distribution of remaining energy to photosynthesis and canopy layer, and uncertainty in the measurement of the energy fluxes by the instruments (Twine et al., 2000; Cook et al., 2004). However, an energy balance closure observed in this study confirms the quality of eddy covariance data for further analysis.

**Phenology**

Phenological properties were measured from June once the plant stand was significant. The length of the growing season in sorghum was 140 days in 2013, 147 days in 2014, and 119 days in 2015. Peak plant height and biomass of both crops differed considerably from each other. Maximum plant height for sorghum was about 140 cm in 2013, and about 130 cm in 2014 and 2015. Leaf area index (LAI) of sorghum varied among three growing seasons. Maximum leaf area in sorghum was observed in August (DOY 213-243), once the flag leaf was fully open and crop was flowering. Peak LAI observed in sorghum was 4.1 in 2013, 7.1 in 2014, and 5.1 in 2015 (refer to chapter 1). Higher plant density in 2014 (11 plants $m^{-2}$) as compared to 2013 (8.3 plants $m^{-2}$) and

2014 (9.3 plants $m^{-2}$) was observed in sorghum. Peak aboveground biomass in sorghum was achieved in about 100 days. Maximum aboveground biomass of the sorghum was about 18, 21 and 25 tons $ha^{-1}$ in 2013 (DOY 263), 2014 (DOY 266), and 2015 (DOY 256), respectively (Fig. 3.3). Maximum above ground biomass was observed when the crop attained physiological maturity.

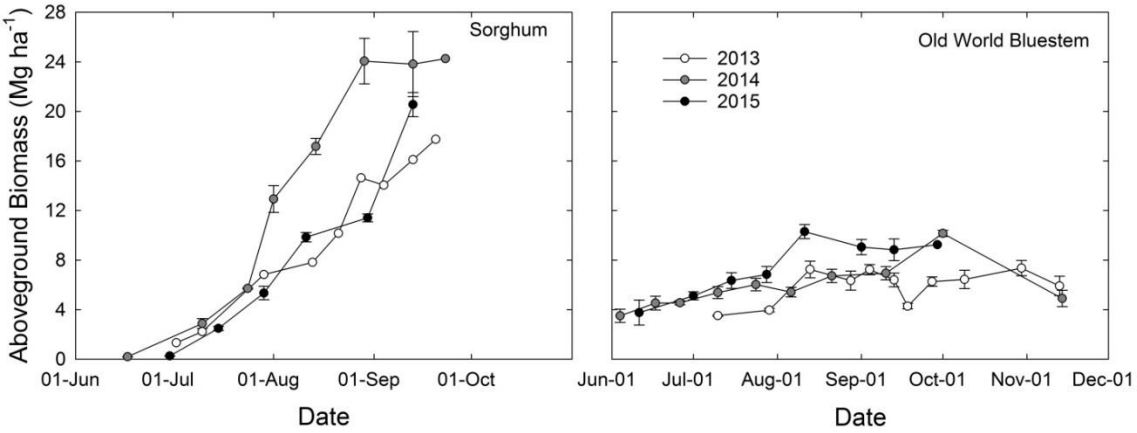


**Figure 3.3: Average above ground biomass in sorghum and old world bluestem. Measurements was started in June once the significant biomass was accumulated in the fields. Error bars represent standard error. Three replications were conducted in sorghum in 2014 and 2015, and 4 replications in old world bluestem during all growing seasons. No replications were done in 2013 in sorghum field.**

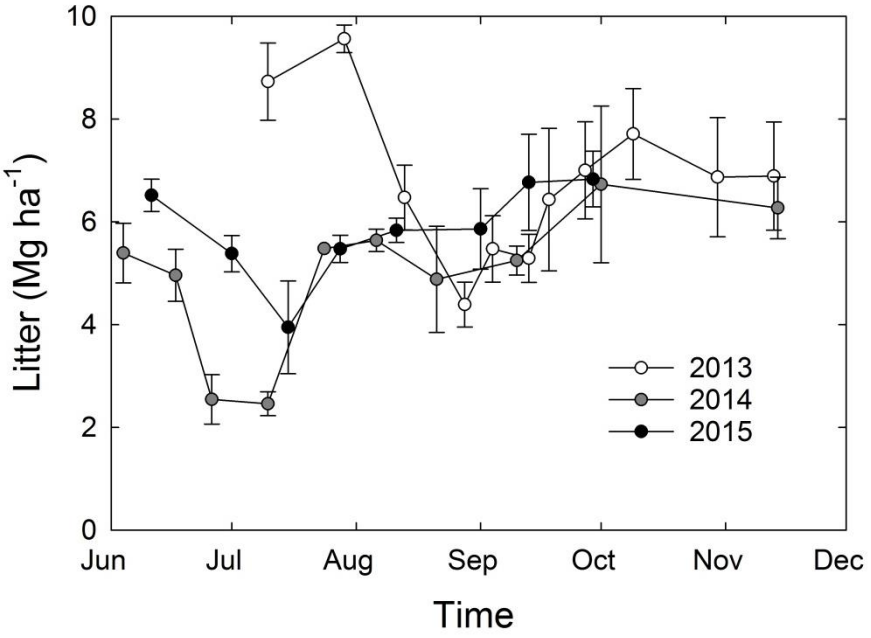


**Figure 3.4: Evolution of litter over the course of growing season in old world bluestem. Error bars represent standard error. Four replications were conducted during each sampling.**

Old World Bluestem achieved a maximum height of about 75-90 cm in 2013 and 2015 and reached up to 110 cm in 2014. Peak aboveground biomass (Green+Yellow leaves) for different seasons was achieved at different times. Maximum biomass observed in OWB was about 7.3, 10.2, and 10.3 Mg $ha^{-1}$ in 2013 (DOY 303), 2014 (DOY 274), and 2015 (DOY 223), respectively (Fig. 3.3). Maximum green leaf biomass achieved in OWB was 4.3, 7.0, 7.6 Mg $ha^{-1}$ on same days of maximum aboveground biomass. Rigorous growth in early season of 2015 contributed to greater green biomass in 2015. Old world bluestem bloomed in 2014, whereas no significant bloom was observed in 2013 or 2015. Old World bluestem goes through stem elongation during

bloom in September-October, which explains greater height and added biomass in crop towards the end of the season. No leaf area measurements were made in OWB. Additionally, we collected litter samples from the OWB field from same points where green and yellow leaf samples were collected. During all years of study, the litter amount followed a declining trend from a higher amount at beginning of the growing season to low values during peak growing period and then ascending again towards the end of the season (Fig. 3.4). Maximum amount of litter was noticed early in the season on DOY 210 (DOY 9.6 Mg $ha^{-1}$) in 2013, on DOY 155 (5.4 Mg $ha^{-1}$) in 2014, on DOY 162 (6.5 Mg $ha^{-1}$) in 2015. Lowest amount of the litter was recorded at the peak growth period on DOY 240 (4.4 Mg $ha^{-1}$), DOY 191 (2.5 Mg $ha^{-1}$) in 2014, and DOY 209 (3.9 Mg $ha^{-1}$) in 2015. Amount of litter at final sampling of the season in the field was 6.9 Mg $ha^{-1}$ (DOY 303) in 2013, 6.3 Mg $ha^{-1}$ in 2014 (DOY 317) and 6.8 Mg $ha^{-1}$ in 2015 (DOY 272).

**Non-Growing Season Carbon Fluxes**

The inter-annual and seasonal carbon fluxes differed considerably between the two agroecosystems (Fig. 3.5). Non-growing season for grassland was from January to April in spring and November-December in fall, whereas for sorghum it stretched (mid-October to May) from harvest to planting in next year. Presence of annual weeds (horseweed: *Erigeron canadensis*) generated slight photosynthetic activity in both fields, though $R_{eco}$ was the dominant carbon flux during non-growing season. The average non-growing season NEE value in sorghum was 0.9 g C $m^{-2}$ $day^{-1}$ in 2014 and 1.7 g C $m^{-2}$ $day^{-1}$ in 2015. Average $R_{eco}$ in sorghum through non-growing season was 2.3 g C $m^{-2}$

$day^{-1}$ in 2013 and 2014, 2.9 g C $m^{-2}$ $day_{-1}$ in 2015. Net cumulative carbon release was 90 g C $m^{-2}$ in 2013, 191.4 g C $m^{-2}$ in 2014 and 368.8 g C $m^{-2}$ in 2015 from sorghum field through the non-growing season. It should be noted that the non-growing season for sorghum in 2013 was only for November and December, whereas 2014 and 2015 include January to April and November-December. On the other hand, average non growing season NEE in grassland was 0.1 g C $m^{-2}$ $day^{-1}$, 0.3 g C $m^{-2}$ $day^{-1}$ and 0.5 g C $m^{-2}$ $day^{-1}$ in 2013, 2014 and 2015, respectively. Average $R_{eco}$ in OWB through the non-growing season was 0.9 g C $m^{-2}$ $day^{-1}$ in 2013, 0.9 g C $m^{-2}$ $day^{-1}$ in 2014 and 1.2 g C $m^{-2}$ $day^{-1}$ in 2015. Cumulative NEE in grassland through dormant season was 11.7 g C $m^{-2}$, 50.5 g C $m^{-2}$, and 84.9 g C $m^{-2}$ in 2013, 2014 and 2015, respectively.

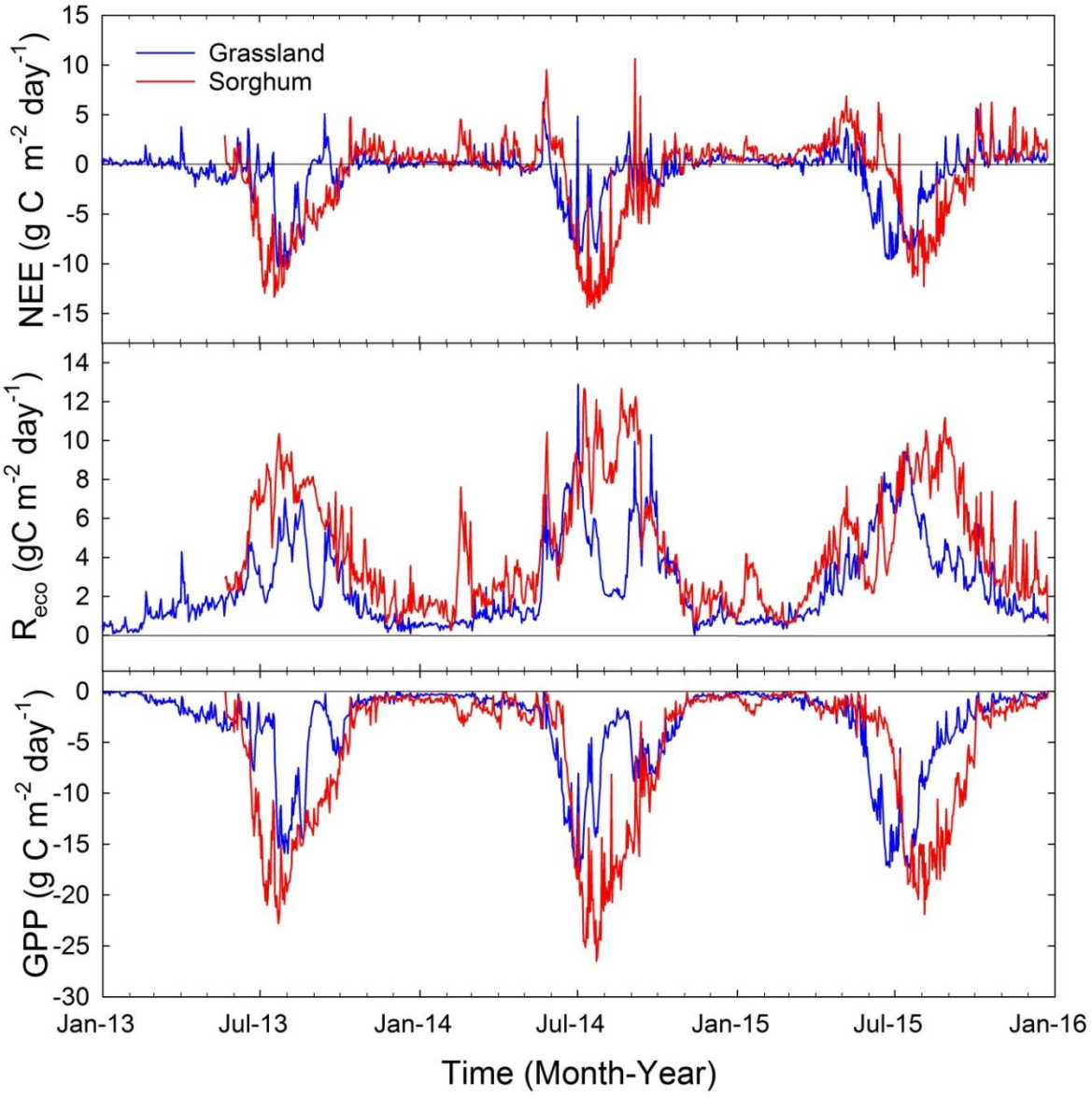


**Figure 3.5. Daily sums of NEE (top), $R_{eco}$ (middle) and GPP (bottom) in old world bluestem site from Jan 1, 2013 to December 25, 2015, and from May 22, 2013 to December 15, 2015 in sorghum.**

**Growing Season Carbon Fluxes**

*Net Ecosystem Exchange:* Figure 3.5 show daily carbon uptakes throughout the study period in OWB field. Variation in seasonal and diurnal trends of carbon uptake was more evident in grass than sorghum during three growing seasons of study (Fig. 3.6, 3.7). Net carbon uptake dynamics of grassland were sensitive to magnitude and timing of precipitation. Average daily net carbon uptake during growing season was -1.7 g C $m^{-2}$ $day^{-1}$ in 2013, -1.7 g C $m^{-2}$ $day^{-1}$ in 2014 and -2.0 g C $m^{-2}$ $day^{-1}$ in 2015. Net carbon uptake picked up in May 2013 using soil moisture stored during winter. However, net carbon uptake was suppressed in June 2013 probably due to declining soil VWC during first half of the month. In May 2014 and 2015, despite initiation of new growth, the grass field acted as a source of carbon, mainly due to greater magnitude of respiration following early season rainfall events and rising soil temperatures. The field transitioned into a strong sink of carbon in June 2014 and 2015. Carbon uptake and $R_{eco}$ declined in August 2014 and September 2015, due to extended dry period. Net carbon uptake declined in October until the field became a net source in non-growing months. Overall the net seasonal uptake of carbon in grassland was -314 g C $m^{-2}$ in 2013, -301 g C $m^{-2}$ in 2014, and -374 g C $m^{-2}$ in 2015 (Table 3.2).

Despite shorter growing season, sorghum had consistently higher seasonal carbon uptake than grass. As a result of irrigation, the seasonal pattern of carbon uptake was similar among all growing seasons (Fig. 3.5). Average daily carbon uptake for sorghum during growing season was -5.0 g C $m^{-2}$ $day^{-1}$, -4.6 g C $m^{-2}$ $day^{-1}$ in 2014, and -3.9 g C $m^{-2}$ $day^{-1}$ in 2013, 2014 and 2015, respectively. Sorghum field remained a weak

source of carbon during early days of growth, especially in 2014 and 2015 following early season rainfalls, before transitioning into a strong sink. The NEE increased gradually until its peak in July and August during active growing season across all the years. The field remained a strong sink until September. Sorghum accumulated -710.3 g C $m^{-2}$, -665.3 g C $m^{-2}$, and -471 g C $m^{-2}$ in 2013, 2014, and 2015, respectively.

Diurnal patterns of carbon uptake during active growing season are presented in figure 3.6 for OWB and figure 3.7 for sorghum. In OWB, net carbon uptake rates during daytime were low in May during all growing seasons. The carbon uptake rates improved following rainfall in June 2014 and 2015. Net carbon uptake rate further improved in July for all growing seasons. In fact, maximum mean monthly net carbon uptake rates of season were observed in July for year 2014 (-21.1 µmol $m^{-2}$ $s^{-1}$) and 2015 (-28.3 µmol $m^{-2}$ $s^{-1}$) (Fig. 5). For 2013, the maximum mean monthly net carbon uptake rate (-20.0 µmol $m^{-2}$ $s^{-1}$) was observed in August following precipitation events in late July and in mid-August. On the contrary, the NEE declined in August 2014 and 2015 following dry and warm conditions. Photosynthetic activity declined in September 2013 and 2015, as a result the site transitioned into weak source of carbon (Fig. 3.5). The field remained a weak sink of carbon in September and October 2014.

Figure 3.6 shows diurnal variation of carbon exchange during active growing period in sorghum. Monthly diurnal patterns of sorghum were consistent during all growing seasons. Maximum mean monthly carbon uptake rate was always greater in sorghum in comparison to OWB. Rapid growth period was observed in June 2013, 2014 and 2015. Monthly average peak NEE values observed were -38.7 µmol $m^{-2}$ $s^{-1}$ in July

2013, -47.7 µmol $m^{-2}$ $s^{-1}$ in July 2014, and -28.9 µmol $m^{-2}$ $s^{-1}$ in August 2015. The carbon uptake declined slightly following peak carbon uptake month and was further depressed in September and October, once irrigations was stopped in second week of September.

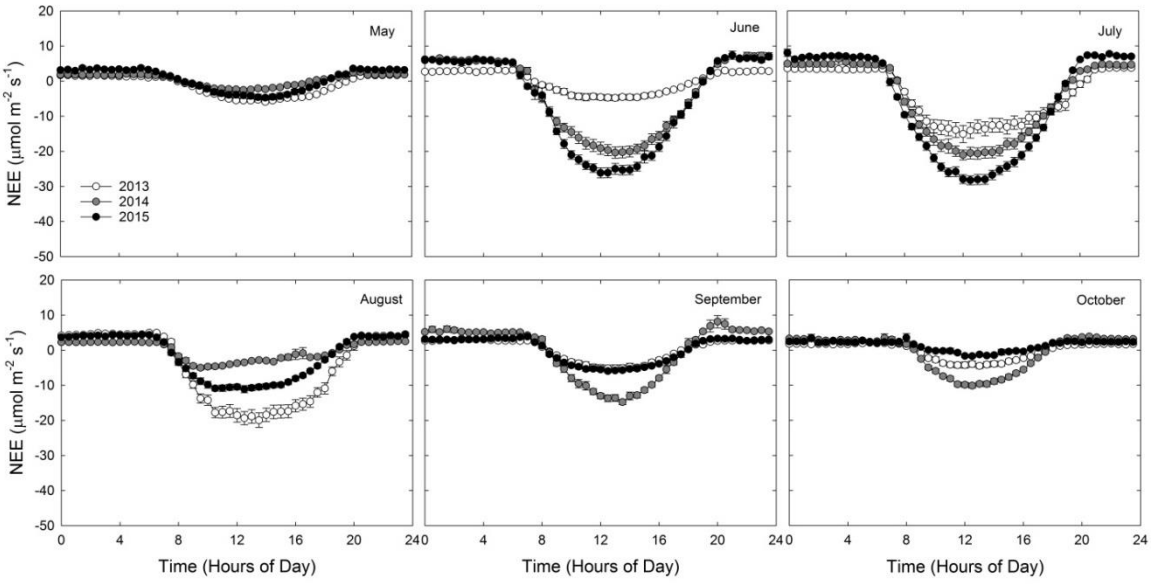


**Figure 3.6. Monthly average diurnal trends of net ecosystem exchange (NEE) in old world bluestem field. The error bars represent the standard error.**

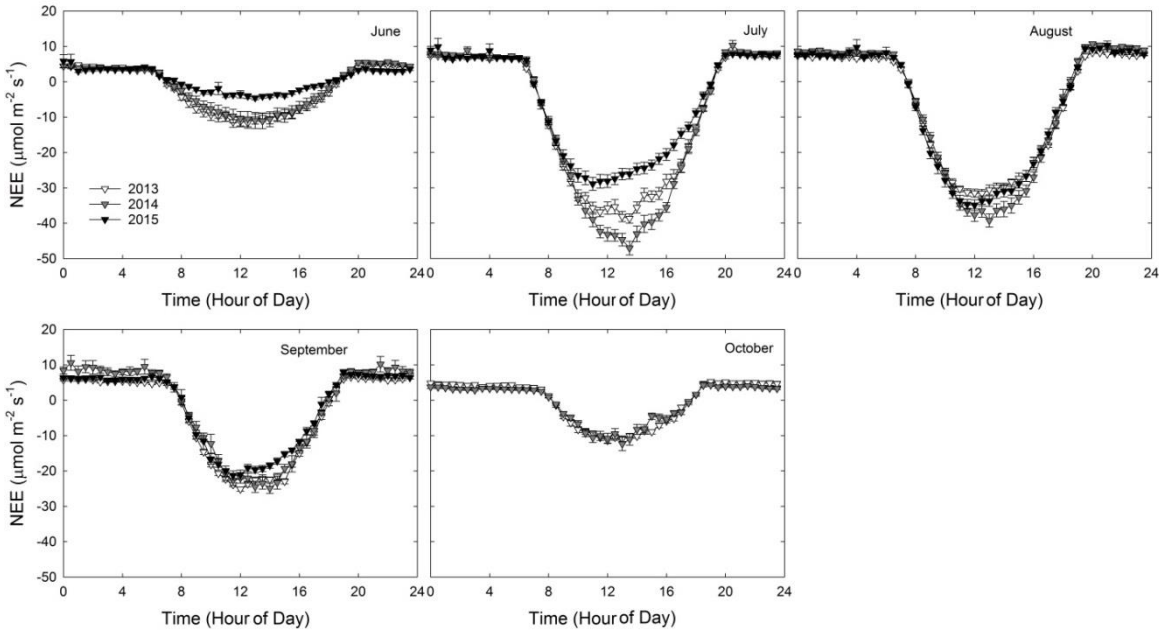


**Figure 3.7: Monthly average diurnal trends of net ecosystem exchange (NEE) in sorghum field. Month of May is not included as the crop was just emerging in that month or was not planted (in 2015). Only days before harvest were included during month of October i.e. 8 days in 2013 and 14 days in 2014. The error bars represent the standard error.**

*Gross primary production:* Daily sums of GPP are presented in Figure 3.5 for OWB and sorghum. The photosynthetic activity of OWB started around first week of May and continued until October through all years of study. Seasonal trends of daily GPP imitated the trends of the NEE once the field transitioned into a net carbon sink. Trends of daily GPP did not follow the NEE during early growing season (before fields transitioned to net sink) as the latter was dominated by $R_{eco}$ in both grassland as well as sorghum. Old World bluestem registered an average daily GPP of -4.8 g C $m^{-2}$ $day^{-1}$ in 2013, -6.2 g C $m^{-2}$ $day^{-1}$ in 2014, and -6.7 g C $m^{-2}$ $day^{-1}$ in 2015. Since the photosynthetic activity in

grassland started earlier than sorghum, the GPP of grassland dominated that of sorghum in May and June in 2014 and 2015 as the latter was not planted or plants were still small. Maximum daily GPP recorded in OWB was -15.9 g C $m^{-2}$ in 2013 (DOY 214), -17.7 g C $m^{-2}$ in 2014 (DOY 185), and -17.3 g C $m^{-2}$ in 2015 (DOY 199). Gross primary production declined as the season progressed in September and October. In our study, OWB recorded -877.2 g C $m^{-2}$ in 2013, -1140.1 g C $m^{-2}$ in 2014, and -1233.5 g C $m^{-2}$ in 2015.

Average daily GPP in sorghum was -11.4 g C $m^{-2}$ $day^{-1}$ in 2013, -12.2 g C $m^{-2}$ $day^{-1}$ in 2014, and -11.3 g C $m^{-2}$ $day^{-1}$ in 2015. Gross primary production of sorghum dominated OWB during active growing months of July, August and September mainly due to frequently replenished soil moisture through irrigations. Maximum daily GPP recorded for sorghum was -22.8 g C $m^{-2}$ (DOY 203) in 2013 and -26.4 g C $m^{-2}$ (DOY 204) in 2014, and -21.9 g C $m^{-2}$ (DOY 216) in 2015. Cumulative GPP of the season was also greater for sorghum in all years of study than OWB. Gross primary production varied among the growing season due to length of the growing season in sorghum. Overall the seasonal GPP of sorghum was -1591.9 g C $m^{-2}$ in 2013, -1780.9 g C $m^{-2}$ in 2014, and -1353.7 g C $m^{-2}$ in 2015.

*Ecosystem Respiration:* Magnitudes of $R_{eco}$ were greater during growing season than that of non-growing season due to rising soil temperatures and added plant respiration (Fig. 3.5). Seasonal respiration in sorghum was similar in 2013 and 2015, while 2014 growing season registered about 30% higher $R_{eco}$. On the other hand, seasonal respiration in OWB in 2014 and 2015 was about 30.0% and 33.0% higher than that recorded in 2013.

Average daily respiration in OWB was 3.1 g C $m^{-2}$ $day^{-1}$ in 2013, 4.5 g C $m^{-2}$ $day^{-1}$ in 2014, and 4.7 g C $m^{-2}$ $day^{-1}$ in 2015. Average daily respiration in sorghum was 6.3 g C $m^{-2}$ $day^{-1}$, 7.8 g C $m^{-2}$ $day^{-1}$, and 7.4 g C $m^{-2}$ $day^{-1}$ in 2013, 2014 and 2015, respectively. Seasonal $R_{eco}$ followed the seasonal trend of GPP in both crops except in May 2014 and 2015. Highest $R_{eco}$ recorded in sorghum was 10.3 g C $m^{-2}$ $day^{-1}$ in 2013 (DOY 204), 12.8 g C $m^{-2}$ $day^{-1}$ (DOY 248) and 10.5 g C $m^{-2}$ $day^{-1}$ in 2015 (DOY 239). Highest daily $R_{eco}$ recorded in OWB was 7.0 g C $m^{-2}$ $day^{-1}$ in 2013 (DOY 211), 12.8 g C $m^{-2}$ $day^{-1}$ in 2014 (DOY 164), and 9.4 g C $m^{-2}$ $day^{-1}$ in 2015 (DOY 192). Overall the cumulative seasonal $R_{eco}$ in sorghum was 877.2 g C $m^{-2}$, 1108.7 g C $m^{-2}$, and 867.0 g C $m^{-2}$ in 2013, 2014, and 2015, respectively. For OWB, cumulative seasonal $R_{eco}$ was 562.8 g C $m^{-2}$, 823.2 g C $m^{-2}$, and 860.3 g C $m^{-2}$ in 2013, 2014, and 2015, respectively.

**Annual Fluxes**

Table 3.2 shows the summary of the annual fluxes calculated from sorghum and OWB. Two complete (2014 and 2015) years of sorghum and three (2013, 2014 and 2015) complete years of OWB were available. While the GPP was high during growing season in both fields, volunteer plants and summer/winter annual weeds in both fields contributed a small portion of GPP during non-growing season. Non growing season contributed 9-14% of the total GPP in OWB, and 14-18% in sorghum during complete years. Non-growing season $R_{eco}$ contributed 30% and 44% of total annual respiration in sorghum during 2013 and 2014, respectively. Similarly, non-growing season $R_{eco}$ contributed 22%, 16% and 20% total respiration in OWB field during 2013, 2014, and

2015, respectively. Mean annual GPP and $R_{eco}$ of sorghum was about 70% and 24% greater than that of OWB, respectively.

**Table 3.2. Seasonal and annual cumulative carbon fluxes in old world bluestem and sorghum field. Two complete years were available for sorghum and three complete years were available for old world bluestem. SD is standard deviation.**

| | Year | Sorghum | | | Old World Bluestem | | |
|---|---|---|---|---|---|---|---|
| | | NEE | GPP | $R_{eco}$ | NEE | GPP | $R_{eco}$ |
| | | g C $m^{-2}$ | | | g C $m^{-2}$ | | |
| *Seasonal* | | | | | | | |
| | 2013 | -710.3 | -1591.9 | 872.1 | -314.5 | -877.3 | 562.8 |
| | 2014 | -635.2 | -1780.9 | 1138.4 | -316.9 | -1140.1 | 823.2 |
| | 2015 | -471.5 | -1353.7 | 882.2 | -373.3 | -1233.5 | 860.3 |
| | Mean | -605.6 | -1575.5 | 964.2 | -334.9 | -1083.6 | 748.7 |
| | (SD) | (122.1) | (214.1) | (150.9) | (18.3) | (184.7) | (162.1) |
| *Annual* | | | | | | | |
| | 2013* | - | - | - | -301.9 | -1023.6 | 721.6 |
| | 2014 | -444.8 | -2084.7 | 1632.6 | -265.6 | -1250.3 | 984.7 |
| | 2015 | -51.4 | -1654.0 | 1602.6 | -287.2 | -1358.7 | 1071.5 |
| | Mean | -248.1 | -1869.4 | 1617.6 | -284.9 | -1210.8 | 925.0 |
| | (SD) | (278.1) | (304.5) | (21.2) | (18.3) | (171.0) | (182.2) |

On inter-annual basis, $R_{eco}$ in OWB was comparable in 2014 and 2015, and about 30% greater than $R_{eco}$ in 2013. Year 2015 (-1233.5 g C $m^{-2}$), recorded the highest GPP followed by 2014 (-1140.1 g C $m^{-2}$) and 2013 (-877.3 g C $m^{-2}$) in OWB. Despite smaller GPP year 2013 recorded NEE comparable to NEE in 2014. Owing to greater growth in 2015, OWB recorded maximum annual carbon uptake in 2015. On the other hand, sorghum registered greater annual $R_{eco}$, GPP and NEE in 2014 in comparison to 2015. It

should be noted that growing season in 2015 was 27 days shorter than 2014. However, proportionally higher $R_{eco}$ in 2015 than 2014 led to greater carbon loss in that year leading to lower NEE. Mean annual NEE of sorghum was 15% smaller than that of OWB mainly due to low net carbon uptake in 2015. Despite higher growth rates sorghum registered lower net carbon uptake than OWB probably because of lower $R_{eco}$. The mean annual (2014 and 2015) net carbon budget of sorghum was -248.1 g C $m^{-2}$. Similarly, mean annual net carbon uptake for OWB was -285.2 g C $m^{-2}$ for the three complete years of study.

**Environmental Controls**

In both crops photosynthetic activity was sensitive to PAR under optimum soil moisture conditions. Since sorghum was irrigated regularly, dry conditions hardly prevailed during active growing season in sorghum. However, periodic dry conditions were evident in grassland. Sudden dips in daily GPP were conspicuous on cloudy or rainy days in both fields. Understanding the crops response to environmental controls such as PAR at the peak photosynthetic activity period is important as it is critical period for biomass production (Oikawa et al., 2015). Figure 3.8 shows the light response curves of sorghum and OWB during peak photosynthetic activity of the season. A rectangular hyperbolic relationship was fitted between PAR and GPP at peak photosynthetic activity time (Figure 3.8). The apparent quantum yield measured in sorghum was -0.045, -0.042, and -0.056 in 2013, 2014 and 2015, respectively. As mentioned earlier, saturation of rectangular hyperbola is relatively slower, therefore the maximum possible values calculated by the models are implausible (Owen et al., 2007). In order to calculate the

$GPP_{max}$, we used the method proposed by Owen et al. (2007), where parameters calculated by the model were used to obtain $GPP_{max}$ at PAR level of 2000 µmol $m^{-2}$ $s^{-1}$ (notated as $(GPP_{max})_{2000}$). Maximum GPP $(GPP_{max})_{2000}$ calculated for sorghum was -53.0 µmol $m^{-2}$ $s^{-1}$ in 2013 and 2015, and -65.5 µmol $m^{-2}$ $s^{-1}$ in 2014. Slightly greater $(GPP_{max})_{2000}$ in 2014 could be attributed to greater leaf area in that year. Similarly, light use efficiency in OWB was -0.032 in 2013, -0.048 in 2014 and -0.040 µmol $CO_2$ per unit µmol of photons. Similarly, $(GPP_{max})_{2000}$ was similar at peak photosynthetic activity for OWB. Maximum GPP recorded during this period in OWB was -43.3 µmol $m^{-2}$ $s^{-1}$ for 2013 and 2014, and -45.3 µmol $m^{-2}$ $s^{-1}$ in 2015.

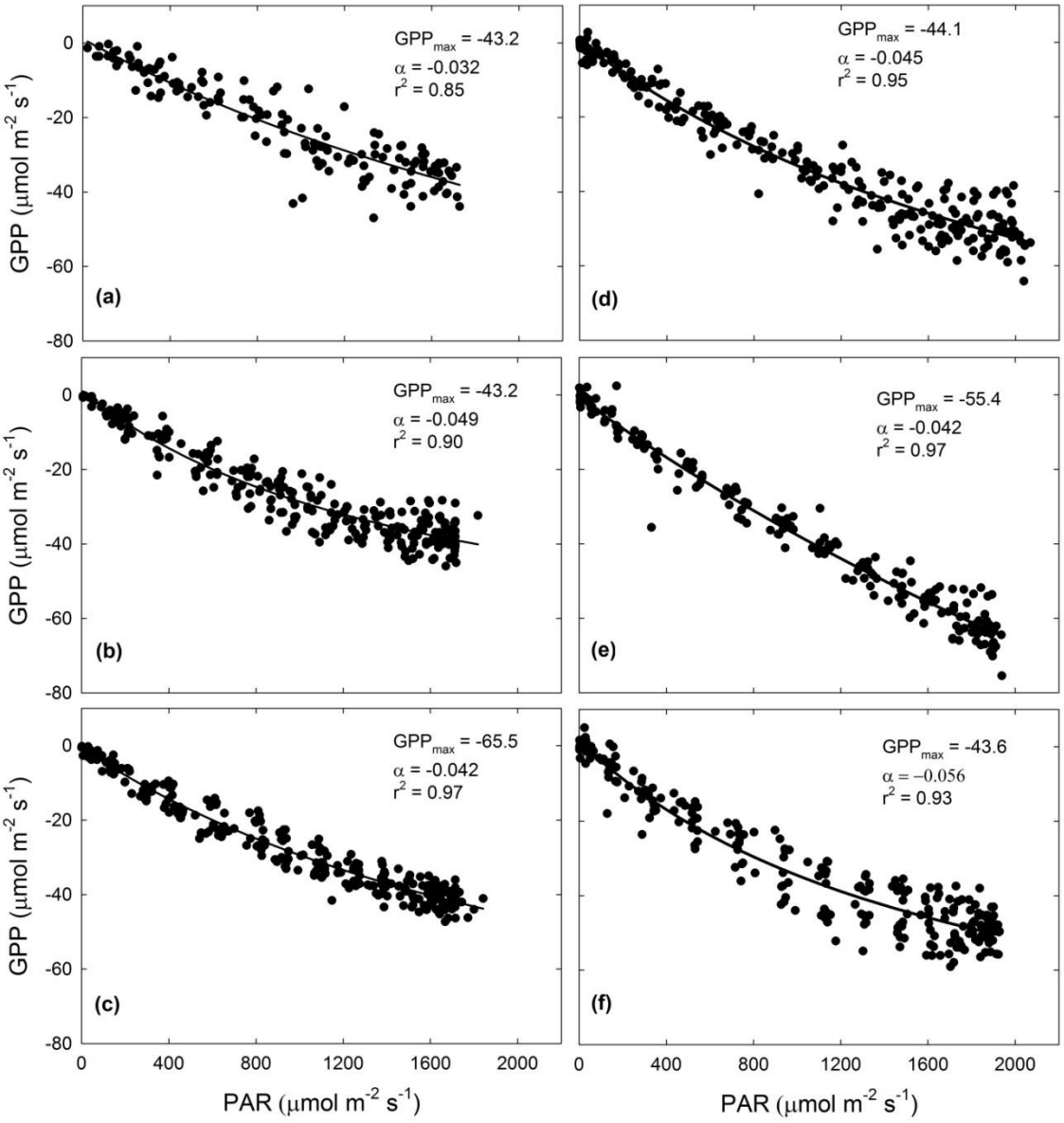


**Figure 3.8: Light response curves of old world bluestem (a, b, c representing 2013, 2014 and 2015, respectively) and sorghum (e, f, g representing 2013, 2014 and 2015, respectively) at peak photosynthetic activity phase of the growing season. Seven to ten clear days were selected from each growing season; crops were at the same phenological stage with no soil moisture stress. However, LAI for sorghum was different at this stage (3.8 in 2013, 5.8 in 2014, and 4.8 in 2015). Only original data was used for this analysis.**

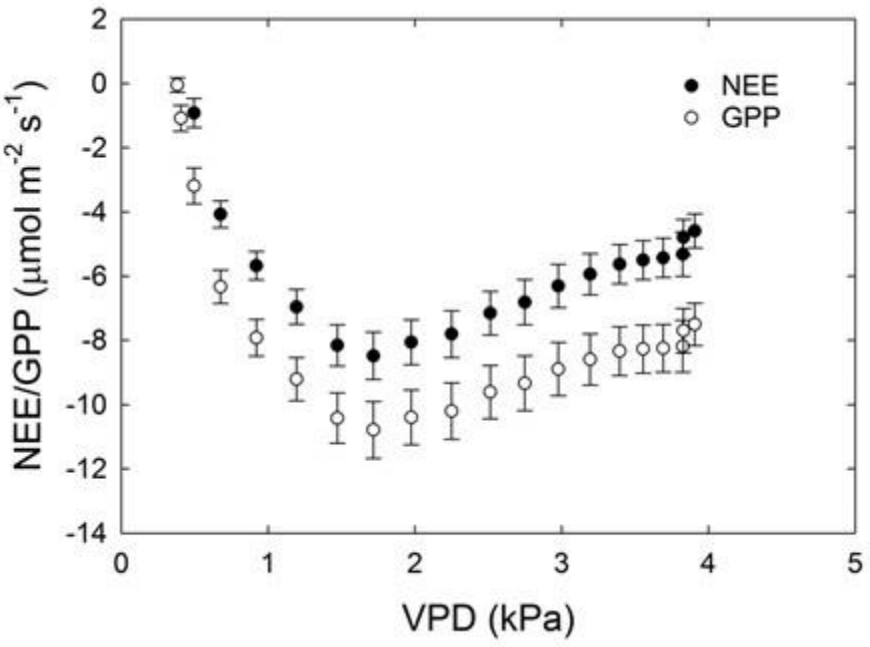


**Figure 3.9: Relationship between half-hourly diurnal averages of Net Ecosystem Exchange (NEE) and Gross Primary Production (GPP) with corresponding VPD during warm and dry conditions (VWC 0.19 $m^3$ $m^{-3}$) in old world bluestem field. Error bars represent the standard error of the mean.**

Conversely, carbon uptake potential of OWB declined during dry and warm condition of dry months. Figure 3.9 shows the rise in carbon uptake in OWB with rising VPD during early morning hours before declining in the afternoon with increasing VPD. Net ecosystem exchange and GPP under warm and dry conditions (during growing season) were aggregated over three growing seasons and plotted against aggregated VPD. Average soil volumetric water content at 10 cm depth was 0.19 $m^3$ $m^{-3}$ during these days. Carbon uptake peaked in between up to 1.7 kPa and declined thereafter. No considerable inhibition of carbon uptake was observed in sorghum during active growing season of 2013 and 2014 as the field was irrigated regularly.

## DISCUSSION

High growth rates and drought tolerance make sorghum and OWB fit for production as major bioenergy crops in the Southern Great Plains. In this study, consistently higher carbon uptake rates were found in irrigated sorghum, an annual crop over rainfed OWB, a perennial bunch grass. Similarly, high carbon uptake rates in sorghum have been reported by Oikawa et al. (2015) for irrigated sorghum in California. Mean seasonal NEE values for sorghum in our study are almost double than those reported by Wagle et al. (2015) for rainfed biomass sorghum. Wagle et al. (2015) attributed the suppression of carbon uptake in sorghum during warm and dry conditions due to rising VPD. No significant reduction in photosynthetic activity due to rising VPD was noticed in sorghum in our study, due to continuous water supply through irrigation. Mean seasonal carbon uptake for OWB in this study are higher than those reported by Rajan et al. (2013) (164 g C $m^{-2}$) for the same site in normal precipitation year (2010). During the time Rajan et al. (2013) conducted this study, the field was grazed three times during growing season, which may explains lower NEE values in their findings. However, mean seasonal NEE for OWB under dryland conditions are comparable to seasonal NEE of rainfed sorghum reported by Wagle et al. (2015) (-261 ±48 g C $m^{-2}$ and -330 ± 45 g C $m^{-2}$) in Oklahoma during two years (dry year and wet year) of study. This finding in our study is important as it suggests that under rainfed conditions in normal rainfall years the OWB can match the carbon uptakes of rainfed sorghum. Seasonal NEE values reported in our study are in good terms with those reported for specific biomass crops by Wagle et al. (2015) for switchgrass in Oklahoma, Eichelmann et al. (2016) for

switchgrass in Canada, Zeri et al. (2011) for switchgrass and miscanthus, and Chocubhair et al. (2015) for miscanthus in Ireland (Table 3.3). in different regions of United States and other countries. Annual NEE for sorghum and OWB in our study matched well with to those of -268 g C $m^{-2}$ and -344 g C $m^{-2}$ reported for native prairies by Suyker and Verma (2004) in Oklahoma and Zeri et al. (2011) in Illinois, respectively (Table 3.3).

**Table 3.3. Seasonal net ecosystem exchange (NEE) as reported in different studies for different bioenergy crops.**

| Authors | Crop | Region | NEE (g C m-2) |
|---|---|---|---|
| Wagle et al. (2015) | Switchgrass | Oklahoma | -406 |
| Wagle et al. (2015) | Swtichgrass | Oklahoma | -490 |
| Eichelmann et al. (2016) | Switchgrass | Canada | -540 |
| Zeri et al. (2011) | Switchgrass | Illinois | -485 |
| Zeri et al. (2011) | Maize | Illinois | -307 |
| Zeri et al. (2011) | Miscanthus | Illinois | -405 |
| Choncubhair et al. (2016) | Miscanthus | Ireland | -411 |
| Suyker and Verma (2004) | Native prairie | Oklahoma | -268 |
| Zeri et al. (2011) | Native prairie | Illinois | -344 |

Carbon exchange properties of OWB were sensitive to the precipitation. Old world bluestem showed a typical C4 grass response to relatively warm and wet summers in 2014 and 2015, with increased photosynthetic activity and biomass production during May-July (Teeri and Stowe, 1976). However, prevailing warm and dry conditions in June 2013, August 2014 and September 2015 limited the carbon uptake potential of the crop. This is in good agreement with findings of Rajan et al. (2013). The authors showed

the transition of this field from net sink of carbon in a good rainfall year to a net source of carbon in a drought year. Inhibition of GPP and NEE with rising VPD under warm and dry conditions can be explained by mechanism of stomatal closer in order to conserve water, thereby increasing stomatal resistance to $CO_2$ diffusion and limiting the carbon uptake and greater respiration rate in the afternoon (Lasslop et al., 2010; Wagle et al., 2014). Similar observations have been reported for sorghum and switchgrass under warm and dry conditions by Wagle et al. (2015) in Oklahoma. Oikawa et al. (2015) reported inhibition in carbon in sorghum under irrigated conditions when analysis between VPD and NEE was conducted on complete dataset. The authors attributed inhibition to carbon uptake to high temperature in the region which reached to 45.7 $^{o}$C, whereas in our study the maximum temperature in three years approached about 40 $^{o}$C. Oikawa et al. (2015) could not find any inhibition of the NEE at peak growth stages when soil moisture was not limited. However, no considerable limitation of carbon uptake was noticed in sorghum in our study as dry conditions hardly prevailed. This is an important observation from our study, as susceptibility of this region to periodic droughts along with uncertain future of irrigation may have implications on future of both crops as sustainable bioenergy crops.

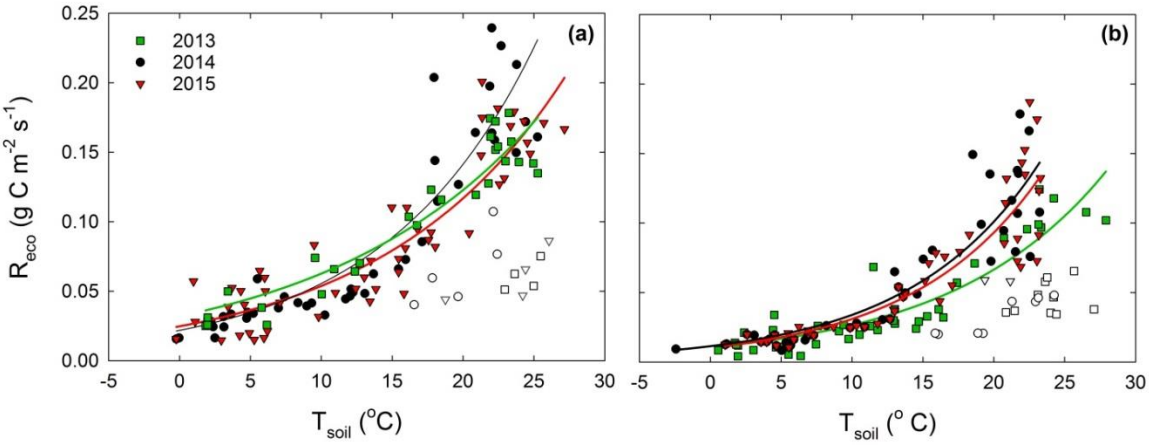


**Figure 3.10: Relationship between average weekly nighttime $R_{eco}$ (g C $m^{-2}$) against average soil temperature ($T_{soil}$ in °C) at 5cm depth for (a) sorghum in 2013 ($R_{eco} = 0.0320e^{0.0672T_{soil}}$)), 2014 ($R_{eco} = 0.0241e^{0.0934T_{soil}}$) and 2015 $R_{eco} = 0.0248e^{0.0776T_{soil}}$ (b) OWB for 2013 ($R_{eco} = 0.0107e^{0.0915T_{soil}}$), 2014 ($R_{eco} = 0.0114e^{0.1090T_{soil}}$) and 2015 ($R_{eco} = 0.0103e^{0.0110T_{soil}}$). $R^2$ ranged from 0.81-0.89 during all years. White circles/triangles/squares represent the $R_{eco}$ during dry conditions (VWC <0.19 $m^3$ $m^{-3}$) for respective years.**

Annual net carbon budget of sorghum was lower in 2015 than 2014, mainly because of lower carbon uptakes due to smaller growing season. Another reason for lower net carbon uptake is due to proportionally higher carbon release into the atmosphere in 2015 than 2014. Major portion of the non-growing season $R_{eco}$ was during early growing season in 2015. Temperature and moisture are well known controlling factors of the $R_{eco}$ and have reported in several previous research studies (Xu and Qi, 2001; Janssens and Pilegard, 2003; Xu and Baldocchi, 2004; Suyker and Verma, 2012; Rajan et al., 2013). When plotted against nighttime temperature, weekly average $R_{eco}$ showed a strong exponential dependence on soil temperature (Fig. 3.10). The temperature sensitivity or $Q_{10}$ values for sorghum was 1.9, 2.6, and 2.2 in 2013, 2014

and 2015, respectively. However, $R_{eco}$ declined when VWC was in the range of wilting point (0.19 $m^3$ $m^{-3}$) point. Majority of the early non-growing season in 2014 remained relatively dry and thus respiration from the site was lower in 2014 than in 2015. Infact, Suyker and Verma (2012) and Rajan et al. (2013) reported similar observations of declining $R_{eco}$ under low soil moisture conditions. In a normal precipitation year, Rajan et al. (2013) reported about 750 g C $m^{-2}$ from the same field from DOY 152 to 365, which was in good terms with $R_{eco}$ in this study (786 g C $m^{-2}$) for corresponding period in 2014 in this study.

In comparison to sorghum, the $Q_{10}$ value for the OWB field was 2.6, 3.0, 3.0 in 2013, 2014 and 2015, respectively. However, in our results, sorghum registered greater $R_{eco}$ during non-growing season than OWB. Greater magnitude of carbon released from sorghum could be attributed to longer non-growing season. In addition to abiotic factors $R_{eco}$ is also driven by biotic factors and their interaction with abiotic factors (Flanagan, 2005). Several research studies have reported a positive correlation between $R_{eco}$ and site productivity/photosynthesis (Craine et al., 1999; Janssens et al., 2001; Falgnan, 2005; Wagle et al., 2014). Greater $R_{eco}$ in sorghum despite lower $Q_{10}$ values can be mathematical. The mathematical reason for higher $R_{eco}$ from sorghum despite lower $Q_{10}$ values than OWB is that the initial value of respiration is nearly double in sorghum than OWB. This explains greater $R_{eco}$ in sorghum field during growing season. Our values of $R_{eco}$ are greater than those reported by Suyker and Verma, (2001) for a tallgrass prairie in Oklahoma. In both crops, $R_{eco}$ surged and peaked in the months when GPP peaked

and declined with the depressing carbon uptake and declining temperatures towards the end of the season.

Biomass production is an important parameter for the bioenergy crops. In this study, biomass production of sorghum was of the same order of magnitude reported by Cotton et al., (2013) (13 to 30 tons $ha^{-1}$) in the Texas High plains, Oikawa et al. (2015) (43.7 tons $ha^{-1}$) from three harvests of single crop within one year in California, Wagle et al. (2015) (30 tons $ha^{-1}$) in Oklahoma for rainfed crop, Singh et al. (2012) (19.4 tons $ha^{-1}$) in Florida, Hallam et al. (2001) (16 ton $ha^{-1}$), and Propheter et al. (2010b) (26.2 tons $ha^{-1}$). On the other hand, biomass production of OWB was of the same order as reported by Dalrymple, (1991) (15 tons $ha^{-1}$) and Griffith et al. (2011) (for *B. ischaemum*), and Buttrey and Bean, (2011). In comparison to specific biomass crops, biomass production in OWB is lower than what has been reported for switchgrass and *miscanthus* in several studies. For example, Wagle et al. (2015) reported 17 tons $ha^{-1}$ and 13 tons $ha^{-1}$ in two years of their study for switchgrass under dryland conditions. Eichelmann et al. (2016) reported an average of 12 tons $ha^{-1}$ of biomass production in Canada, Sanderson et al. (1996) reported up to 26 tons $ha^{-1}$ biomass production in Alabama. Green vegetative biomass of sorghum before flowering is used for processing and biofuel production (Saballos, 2008). Wagle et al. (2014) and Cotton et al. (2013) reported the maximum biomass of sorghum by mid-august at heading stage. In our study, the heading stage was achieved in mid-August itself, indicating possibility of an early harvest from sorghum. Also, our results show that sorghum is capable of considerable amount of carbon uptake in August and September under optimum soil moisture conditions. Oikawa et al. (2015)

reported that lesser number of days were required for a ratoon crop of sorghum to achieve peak growth period than a crop grown from seeds. This suggests sorghum in the Southern Great Plains has potential of at least two harvests. This aspect is important as multiple cuttings can ensure continuous supply of feedstock to the refineries. However, additional research will be required to assess the feasibility of such systems in the high plains as the environmental factors change considerably in August and September in the region.

## CONCLUSION

This research assessed and compared on-site carbon dynamics of annual and perennial bioenergy crops in the Southern high Plains. High growth rates and drought tolerance can help sorghum and OWB to become major sources of biofuel feedstock crops in the Southern Great Plains. However, productivity of rainfed OWB will largely depend on rainfall distribution and amount. In our study, both crops were strong sinks of carbon during growing season as well at annual scale. Non-growing season carbon fluxes due to respiration can appreciably affect the annual carbon uptake dynamics of both fields. Soil temperature and moisture were important factors deciding the magnitude of $R_{eco}$ from the fields during non-growing season. It should be noted that different varieties of OWB differ in physiological and phenological characters and hence may show different biomass production potential. Sorghum on the other hand, due to its drought tolerant properties can emerge as major annual crop for biofuel feedstock, as the water requirement of sorghum production is lower than corn. Keeping in mind the large cattle industry and depressing water table in the Ogallala Aquifer in the Texas High

Plains, sorghum and OWB with their drought tolerant and forage properties could emerge as major pasture/silage and biofuel feedstock crops in the region. Early achievement of harvestable biomass gives opportunity of multiple harvests from both crops. In addition to biomass production, conversion efficiency of the feedstock is also an important factor for bioenergy crops. Since, the biomass produced from these fields will be removed in actually biofuel production scenarios, these dynamics are subject to change. Therefore, more research is required to assess the off-site and life-cycle analysis of the bioenergy production systems. More research will also be required to assess the complete environmental services of the OWB and sorghum as bioenergy crops.

# CHAPTER IV

# CARBON DYNAMICS OF BIOENERGY CROPS AND CONVENTIONAL COTTON CROPPING SYSTEMS IN SOUHTERN GREAT PLAINS: IMPLICATIONS OF LAND USE CHANGE ON CARBON BALANCE

## INTRODUCTION

Large scale land use change to bioenergy crops driven by expanding biofuel industries is expected to have significant impact on the global C cycle (Fargione et al., 2010; Searchinger, 2010; Anderson-Teixeira et al., 2013). Most of the land requirement for bioenergy crops will be met from existing cropland, retired croplands/CRP and marginal lands (Fargione et al. 2010; Qin et al., 2012). However, with rapid expansion of croplands in recent times, land itself has become a limited resource (Qin et al., 2012). Land use conversion to cropland itself is expanding at a rate of 3.4 million ha $year^{-1}$ to maintain food security of growing population (FAO, 2010). Expansion of area dedicated to bioenergy crops will not only lead to competition for land between food crops and bioenergy crops, but also for water and energy resources. In the United States itself, it is estimated that 15% of the existing cropland will be converted to bioenergy cropping systems to meet the target of 136 billion liters of biofuel by 2022 (Qin et al., 2012). About 80 billion liters will be produced as second generation lignocellulosic biofuels. By

2014, about 15 billion gallons of biofuel were produced, of which only 25% was contributed by second generation biofuels. Therefore, there is a scope for expansion of second generation bioenergy crops in the United States. Nearly half of this amount will be produced in the South Eastern United States. It is estimated that this production will induce a land use change on about 11% existing croplands in the South-Eastern United States, including the Southern Great Plains (USDA, 2010).

The Southern Great Plains is a semi-arid region with long-term (1911-2005) mean annual rainfall of about 465 mm (Allen et al., 2008). Prior to farming the region was dominated by shortgrass prairie. Discovery of the vast underground Ogallala Aquifer transformed the region to one of the major agricultural regions in the United States (Gould, 1975; Allen et al., 2008; Rajan et al., 2014). The Southern Great Plains is the largest producer of cotton (*Gossypium hirsutum* L.) in the U.S. (Attia et al., 2015). Grain sorghum (*Sorghum bicolor* L.), corn (*Zea mays* L.), and winter wheat (*Triticum aestivum* L.) are other major crops in the region. However, excessive extraction of water for agricultural use has depressed the water table of the Ogallala Aquifer by over 30 m in most parts of the Southern Great Plains (Rajan et al., 2015). Continuous cotton under conventional tillage has been a dominant row cropping system in the Southern Great Plains for several decades (Acosta-Martinez et al., 2010). Low returns of organic matter from cotton cropping systems has depleted the organic matter reserves of the soils in Southern Great Plains and declined the soil quality (Moore et al., 2000; Wright et al., 2008; Allen et al., 2008; Acosta-Martinez, 2010). Soil organic matter accumulation is important for soil health as it improves soil structure, prevents soil erosion, improves

infiltration and water holding capacity, and sequesters atmospheric carbon dioxide (Lal, 2004). Therefore, more sustainable production systems are required which can promise long-term sustainability in terms of carbon sequestration. Sustainability of a system could be assessed from its carbon and energy balance properties (Zenone et al., 2013). Moreover, carbon and energy balance properties of different ecosystems interact differently to the regional environment. Therefore, a large scale land use change from cotton to bioenergy crops will have significant effects on carbon balance of the region.

Bioenergy crops are regarded as carbon neutral crops as the carbon fixed in biomass is lost to atmosphere, however life cycle analysis of carbon budget has been reported the bioenergy crops to be net source or sink of carbon to the atmosphere depending on the vegetation and management practices and processing technologies (Tilman et al., 2006; Cherubini et al., 2009; Johnson, 2009;). Although each step in the life cycle of the biofuels is vital, but it is very important to study the carbon balance of the bioenergy crops in their production systems itself. Several recent studies have reported net carbon sinking capacity of annual and perennial bioenergy crops at ecosystem scale in different parts of North America (Zeri et al., 2011; Wagle et al., 2015; Oikawa et al., 2015; Eichelmann et al., 2015). Bioenergy crops have been reported to improve soil organic matter status depending upon management practices and amount of residues left on the surface after harvest (Halvin et al., 1990; Polley, 1992; Tolbert et al., 2002; Cotton et al., 2013; Qin et al., 2012; Meki et al., 2013). Annual bioenergy crops have been shown to have greater yields than perennial crops during early of years of establishment (Propheter et al., 2010). Perennial bioenergy crops

especially native grasses have added benefits associated with lower resource requirement, lower agronomic management, and ecosystem services linked to wildlife. While, net carbon exchange fluxes of corn, switchgrass and other bioenergy crops have been widely reported, the net carbon exchanges of some less popular potential bioenergy crops such as sorghum and old world bluestem (OWB) have been scarcely reported.

In this study, carbon budget dynamics of a potential annual and perennial bioenergy crop was investigated and compared with conventional cotton cropping system in the Southern Great Plains using eddy covariance systems. Potential bioenergy crops investigated in this study are high biomass forage sorghum and old world bluestem. While, sorghum has established cropping systems for grain and silage production in the Southern Great Plains, OWB is popular as pasture and is one of the most planted crops on CRP lands in this region. Studies regarding direct measurements of carbon exchange between canopy and atmosphere are rare in the Southern Great Plains. Also, in our knowledge this is the first such study investigating carbon exchange dynamics of irrigated and dryland cotton in this region. The main objective of this study was to describe seasonal and annual net carbon exchange dynamics of an established OWB field along with annual bioenergy and conventional row crops in the Southern Great Plains.

## MATERIALS AND METHODS

### Study Site

This study was conducted in four different farmers' fields fitted with central pivot irrigation systems in the Texas High Plains region. The high biomass forage sorghum field, managed for commercial seed production, was located approximately 3.5 miles northeast of Plainview, TX (34°12'34.70'' N and 101°37'50.85'' W, 1100 m elevation). The cultivar planted was Surpass XL *bmr* (brown midrib). Sorghum was planted on one half of the field and the remaining half was planted with cotton (*Gossypium hirsutum* L.). The farmer practiced crop rotation between these crops on both halves of the field. Management practices prior to planting sorghum included mowing down of cotton stubbles after harvesting previous cotton crop followed by tillage in spring and before planting the crop. Total area planted with sorghum each time was about 25 ha. The crop was planted on 20 May in 2013 and 2014 at a seeding rate of 4.9 kg $ha^{-1}$. Heavy rains in late May during 2015 delayed planting, thus the crop was planted on June 4 in 2015 at the same seeding rate. The row spacing in 2013 and 2015 was 40 inches and 20 inches in 2014. Urea was broadcasted in the field in spring before planting at a rate of 150 kg N $ha^{-1}$. In addition, 30 kg $P_2O_5$ $ha^{-1}$ was also applied prior to planting. The field was irrigated with low elevation application center-pivot irrigation system during the crop growth period. For first 40 days the field was supplied with 0.75 inch and for rest of the season it was supplied with 1.5 inch water during each irrigation

event. The field was supplied with about 400 mm of water through irrigation in 2013, about 400 mm in 2014 and about 270 mm in 2015. Also, the field was cultivated in between the plant rows to kill weeds twice in June every year when the crop was still small. The field was harvested for seed on 8 October in 2013, on 14 October in 2014, and on October 1 in 2015. The growing season was 140, 147, and 119 days long for 2013, 2014, and 2015, respectively. Equipment availability and late season rainfall affected the timings of harvest. The field remained fallow post-harvest in winter and spring. The farmer let the remaining stalk grazed by cattle in March 2014 and in January 2015. A fence was put around the tower during the presence of cattle in the field. Since the crop was grown in rotation with cotton, the new crop was planted on other half of the field where cotton was produced in previous season. The major soil mapping unit at the study site is Pullman clay loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with 0 to 1% slope.

The perennial grassland was located about 5 km ($34^{o}$ 08'47" N, $101^{o}$25'48" W) west of Lockney, TX and was established in 2007. The pasture was seeded with WW-B Dahl Old World Bluestem (OWB) (*Bothriochloa bladhii* L.) at the seeding rate of 2.8 Kg seed $ha^{-1}$. "WW-B. Dahl" OWB was released in 1994 jointly by USDA-ARS, USDA-SCS, Texas Tech University, and the Texas Agricultural Experiment Station originally from a selection made in India (Rogers *et al*., 2012). It is a bunchgrass with an upright growth habit and has better drought tolerance and water use efficiency than conventional cropping systems in the Southern Great Plains (Allen *et al*., 2005). Total area of the site is about 42 ha. Until 2011 the field was used for grazing by the cattle or

for seed production. This field was equipped with a center pivot irrigation system; however, no irrigation, nutrient supply or grazing operation was conducted during the study period (2013-2015). The growing season for the crop roughly ranged from May to October. Peak growing season occurred from June to July depending upon precipitation. The grass remained in vegetative state for most part of the growing season and bloomed in late September/early October. The field was harvested for seed on November 14, 2014. No seed harvesting was done in 2013 and 2015. The field was never harvested for hay. Major soil mapping unit in the field was Pullman clay loam with 0-1% slope.

The irrigated cotton field was located adjacent to sorghum field about 4 km north-east of Plainview in Hale county. In 2013, Cotton was planted in first week of June. In 2014, first planting of cotton on May 30 was failed and cotton was replanted on June 9. In 2015, cotton was planted on June 2. Cotton variety planted was Fibermax 2322 at a seeding rate of 40,000 seeds per acre during all years of study. Cotton was applied with 100 Kg $ha^{-1}$ of nitrogen (N) and 35 Kg $ha^{-1}$ of $P_2O_5$ before planting. Total area of cotton planted was about 60 acres. Row spacing was 1 m. The field was irrigated using a center-pivot irrigation system. Cotton was sprayed with defoliator (Ginstar) during last week of October. Cotton was harvested on November 7-8 each year of study. Cotton stubbles were mowed down to about 4 inch height after harvest. Cotton field was planted in rotation with sorghum.

Dryland Cotton field was located about 3 km north of Lockney, TX. Dryland was planted on June 1 in 2013, 2014 and 2015. The crop failed in 2013 and farmer ploughed the field to claim crop insurance. In 2015, the farmer decided to plant grain sorghum in

the field. As a result, the tower was moved to a nearby dryland cotton field. The size of both fields was about 100 acres. The crop was planted with variety Fibermax 2011 during all years of study. Row spacing was 1 m. Crop was planted at seed rate of 26000 seeds per acre. No fertilizer was applied to the field in 2014 and 2015. The field was sprayed with defoliator (Ginstar) on October 21 in 2014. The field was harvested on November 6. In 2015, late season rains damaged the cotton bolls and farmer did not harvest the field.

**Eddy Covariance Data Collection**

Carbon dioxide, water vapor/latent heat (LE) and sensible heat (H) fluxes were measured in the fields using eddy covariance systems. While the eddy covariance system in grassland was established in 2010, the tower in sorghum, dryland cotton and irrigated cotton was established at planting in 2013. Data collection from irrigated cotton started from July 2$^{nd}$ 2013. Both towers were set up in the middle of the all fields, with fetch of about 150 m from all directions. An integrated sonic anemometer (Model CSAT-3A, Campbell Scientific) and infra-red gas analyzer (IRGA, Model EC-150, Campbell Scientific) called the IRGASON was used to measure wind velocity and $CO_2$, $H_2O$ vapor concentration, and H in the ambient atmosphere. In grassland the $CO_2$, $H_2O$ vapor concentration was measured using Li-7500 IRGA (LI-COR Biosciences) and wind velocity and sensible heat flux were measured using sonic anemometer sonic anemometer (Model CSAT-3A, Campbell Scientific). The system was installed in middle of each field with fetch of 150 m or more from all directions. These instruments were set up facing south-southwest (in the prevailing wind direction) at a height of about

2.1 m from ground surface. The height of the instrument was adjusted in sorghum field during growing season with increasing crop height to a final height of about 2.6 m from ground. Other environmental variables measured at both sites included air temperature ($T_{air}$) and relative humidity (RH) (HMP50, Campbell Scientific), net radiation (Kipp & Zonen NR-Lite net radiometer), photosynthetically active radiation (PAR) (LI-200SL quantum sensor, LI-COR), solar irradiance (LI-190SB pyranometer, LI-COR), precipitation (TE525 rain gauge, Campbell Scientific), soil temperature ($T_{soil}$) at 4 cm below the surface (TCAV averaging soil thermocouples, Campbell Scientific), and soil volumetric water content at 4 cm below the surface (CS-616 water content reflectometer, Campbell Scientific). Self-calibrating soil heat flux plates (HFPSC-01, Hukseflux, Campbell Scientific, Logan, UT) were used to measure soil heat flux at 8 cm depth from soil surface. Soil heat storage which is the amount of heat stored in 8 cm soil depth over soil heat flux plates was calculated using the following equation:

$$S = \frac{\Delta T_s C_s d}{t} \qquad [4.1]$$

Where S is the storage term, $\Delta T_s$ is change in surface soil temperature, $d$ is depth of soil in meters above soil heat flux plate, $C_s$ is the heat capacity of moist soil, and $t$ is time in seconds. Heat capacity of soil can be calculated from following equation using bulk density ($\rho_b = 1.3$ gm $cm^{-3}$), volumetric water content ($\theta_v$), density of water ($\rho_w = 1000\ kg\ m^{-3}$), heat capacity of water ($C_w = 4.2\ kJ\ kg^{-1}K^{-1}$), and heat capacity of dry soil ($C_d = 840\ J\ kg^{-1}K^{-1}$):

$$C_s = \rho_b C_d + \theta_v \rho_w C_w \qquad [4.2]$$

Soil heat storage term was calculated using temporal variations in soil temperature and soil moisture in Eq. [4.1] and [4.2]. Soil heat storage term and measured soil heat flux were added to obtain soil heat flux at surface (G).

Infra-red gas analyzer and net radiometer surfaces were cleaned regularly as per manufacturers' guidelines to avoid accumulation of dust. Data from the CSAT3A sonic anemometer and IRGA system were measured at 10-Hz sampling rate using a CR3000 datalogger (Campbell Scientific). All other environmental variables were measured at 5 seconds interval. The datalogger was programmed to calculate and save 30-min average values of all environmental variables. The raw 10-Hz wind velocity and EC150/LI-7500 data were saved for further post-processing and analysis of $CO_2$ and energy fluxes.

**Data Processing and Gap filling**

Data from eddy covariance system was used to calculate half-hourly $CO_2$ and energy fluxes. The flux measured from the eddy covariance tower is the average of the product of the covariance between scalar ($CO_2$, water vapor and temperature) and vector (vertical motions of wind). The high frequency data were analyzed using EddyPro 4.0 software (LI-COR Biosciences, Lincoln, NE). Flux computation requires a series of operations in order to apply corrections to raw data for flux computation. Some of these corrections include spike removal, block averaging, coordinate rotation, spectral corrections for flux losses (Moncrieff et al., 1997), and correction for air density fluctuations (Webb et al., 1980). EddyPro software has built-in functions to apply these corrections and process the eddy covariance data.

Occasional gaps in the flux data occurred during power failure or maintenance were gap filled. In addition, the physically implausible values in the data were also filtered and gap filled. Further, the flux is usually underestimated during low turbulence conditions and therefore, data during low turbulence conditions (when the friction velocity (u*) was <0.10 m $s^{-1}$ (Rajan et al., 2015)) was filtered and gap-filled. In sorghum, the average u* during growing season was 0.31 $ms^{-1}$, 0.33 $ms^{-1}$, and 0.31 $ms^{-1}$ in 2013, 2014, and 2015, respectively. The average u* during growing season in grassland was 0.31 m $s^{-1}$, 0.36 m $s^{-1}$, 0.31 m $s^{-1}$. After screening the data for out of the range and above mentioned filtering criteria, the amount of data which was either missing or did not clear the quality check criteria was about 21%, 8%, and 40% in 2013, 2014, and 2015, respectively. During growing season, 21%, 13 and 3% data was gap-filled in 2013, 2014, and 2015 respectively. The amount of data to be gap filled in grassland was 32, 16 and 25% of the total data in 2013, 2014, and 2015, respectively.

The CarboEurope and Fluxnet eddy covariance gap-filling on-line tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/) was used for gap filling, which is based on the methods similar to those described in Falge et al. (2001) and Reichstein et al. (2005). The data of direct interest such as fluxes is gap filled by averages of ± 7 days windows under similar meteorological conditions when all the meteorological variables are available. The similarity of meteorological conditions is defined when radiation, $T_{air}$ and VPD do not fluctuate beyond threshold values of ±50 W $m^{-2}$, ±2.5 $^{o}$C, and ±0.5 kPa, respectively. This window is expanded to ±14 days, in case similarity in meteorological conditions is not achieved within 7 days window.

Flux partitioning into GPP and $R_{eco}$ were done using empirical model developed from night-time NEE and soil temperature (4 cm) data. Night-time NEE values represent $R_{eco}$, which includes soil and plant respiration. Night time was selected when the global radiation was below 20 W $m^{-2}$ threshold. Daytime $R_{eco}$ was evaluated using an exponential regression model developed between nighttime NEE measurements and corresponding soil temperature ($T_{soil}$) measurements made at the 4-cm depth. The general form of the regression model is:

$$R_{eco} = Ae^{(B*Tsoil)} \qquad [4.3]$$

where A and B are constants evaluated with least squares regression.

Only original measured data was used to parametrize this model. Further, daily $R_{eco}$ and NEE was calculated by integrating daytime and nighttime measurements. Daily gross primary production (GPP) was calculated as:

$$GPP = R_{eco} - NEE \qquad [4.4]$$

Ecosystem respiration includes both heterotrophic and autotrophic respiration. The sign convention used was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

**Energy Balance Closure**

Quality of eddy covariance data is very important and can be determined the energy balance closure (Wilson et al., 2002). The energy balance closure at the site was examined by regressing 30-min $R_n$ data against the corresponding sum of LE, H, and G.

To examine energy balance closure a linear regression was performed between available energy (Rn-G), and energy fluxes of LE and H. While soil heat storage term was calculated as mentioned above, the canopy storage and energy used for photosynthesis was not calculated for this analysis. Good quality original data for LE and H were used to assess energy balance closure when all the energy balance components were available. Physical and biochemical energy storage terms in the crop canopy layer were assumed to be negligible and thus, were not used in the energy balance closure (Wilson et al., 2002). The difference between $R_n$ and G represents the available energy at the surface. Assuming negligible heat storage within the canopy and net horizontal advection of energy, the energy balance can be described as:

$$R_n - G = LE + H \qquad [4.5]$$

The sign convention used for Rn and G are positive when the flux is downwards and negative when the flux is upward. The sign convention used for LE, H and C fluxes was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

**Light Response Curves**

Light response curves were obtained by obtaining relationship between daytime NEE with photosynthetic photon flux density (PPFD). Daytime was differentiated from night when photosynthetic photon flux density (PPFD) was >1 μmol photon $m^{-2}$ $s^{-1}$. To understand the photosynthetic response of the sorghum crop at different growth stages, a rectangular hyperbola model was used (Flanagan et al., 2002; Hussain et al., 2011).

$$GPP = \frac{GPP_{\max} PAR}{PAR + \left(\frac{1}{\alpha}\right) GPP_{\max}} + R \quad [4.6]$$

where $NEE_{max}$ is the maximum NEE rate (μmol $CO_2$ $m^{-2}$ $s^{-1}$), PPFD is the photosynthetic photon flux density (μmol photon $m^{-2}$ $s^{-1}$), α is the initial slope of the light response curve (μmol $CO_2$ $m^{-2}$ $s^{-1}$/μmol photon $m^{-2}$ $s^{-1}$), $NEE_{max}/\alpha$ is the PPFD associated with half of the maximum NEE rate, and R is the intercept term, which is the average daytime $R_{eco}$ (μmol $CO_2$ $m^{-2}$ $s^{-1}$). In the present study, we evaluated Eq. [4.6] at PPFD of 2000 μmol photon $m^{-2}$ $s^{-1}$, and the term $(NEE_{max} + R)_{2000}$ represents the average maximum uptake rate.

**Biometric Data**

Plant dry biomass weight was measured during the growing season. Sorghum, dryland cotton and irrigated cotton plant samples were taken randomly (3 replications) from respective fields to measure leaf area index (LAI), dry leaf mass and dry shoot (including bolls) mass. For grasslands, four random plant samples (for green, yellow leaves and litter) were taken from quarter of a meter area. No LAI measurements were done on the grass samples. Plants were stored in an ice chest in the field and leaf area of sorghum was measured (after separating leaves from shoots) using a leaf area meter (Model LI-3100, Licor Biosciences, Lincoln, NE) immediately after they were brought to the laboratory. For grass samples, green and yellow leaves were separated after samples were brought to the lab. After measuring leaf area, leaves and shoots were stored in paper bags and dried at 65$^{o}$C for one week. Dry mass of shoot and leaves was

taken immediately after removing the dried samples out of the oven. Plant density (number of plants per $m^2$) and leaf area were used to calculate the LAI.

## RESULTS AND DISCUSSION

### Weather

Average monthly maximum air temperature ($T_{air}$) and minimum air temperature is presented in Figure 4.1. Variation in highest and lowest recorded maximum and minimum $T_{air}$ (during active growing season) across all the fields was within ±1 $^{o}$C and ±0.5 $^{o}$C, respectively. Average monthly Maximum $T_{air}$ reached 32 $^{o}$C every year in July. Average monthly minimum $T_{air}$ approached -5.0 $^{o}$C in December in 2013, in January in 2014, and 2015. A cold front passing through the area dropped monthly average maximum $T_{air}$, lower than 30 year mean (26.1 $^{o}$C recorded and 30 year average 28.1 $^{o}$C) in September 2014 and (23 $^{o}$C recorded and 30 year average 27.1 $^{o}$C) May 2015. Mean annual $T_{air}$ of 2014 complete years was lower than (14.0 $^{o}$C in OWB, 14.3$^{o}$ C in dryland cotton, 13.8$^{o}$ C in irrigated cotton, 13.8$^{o}$ C sorghum) 30 year (1981-2010) mean (15.0 $^{o}$C) annual temperature. Mean annual $T_{air}$ in 2015 was close to 30 year mean average in all the fields.

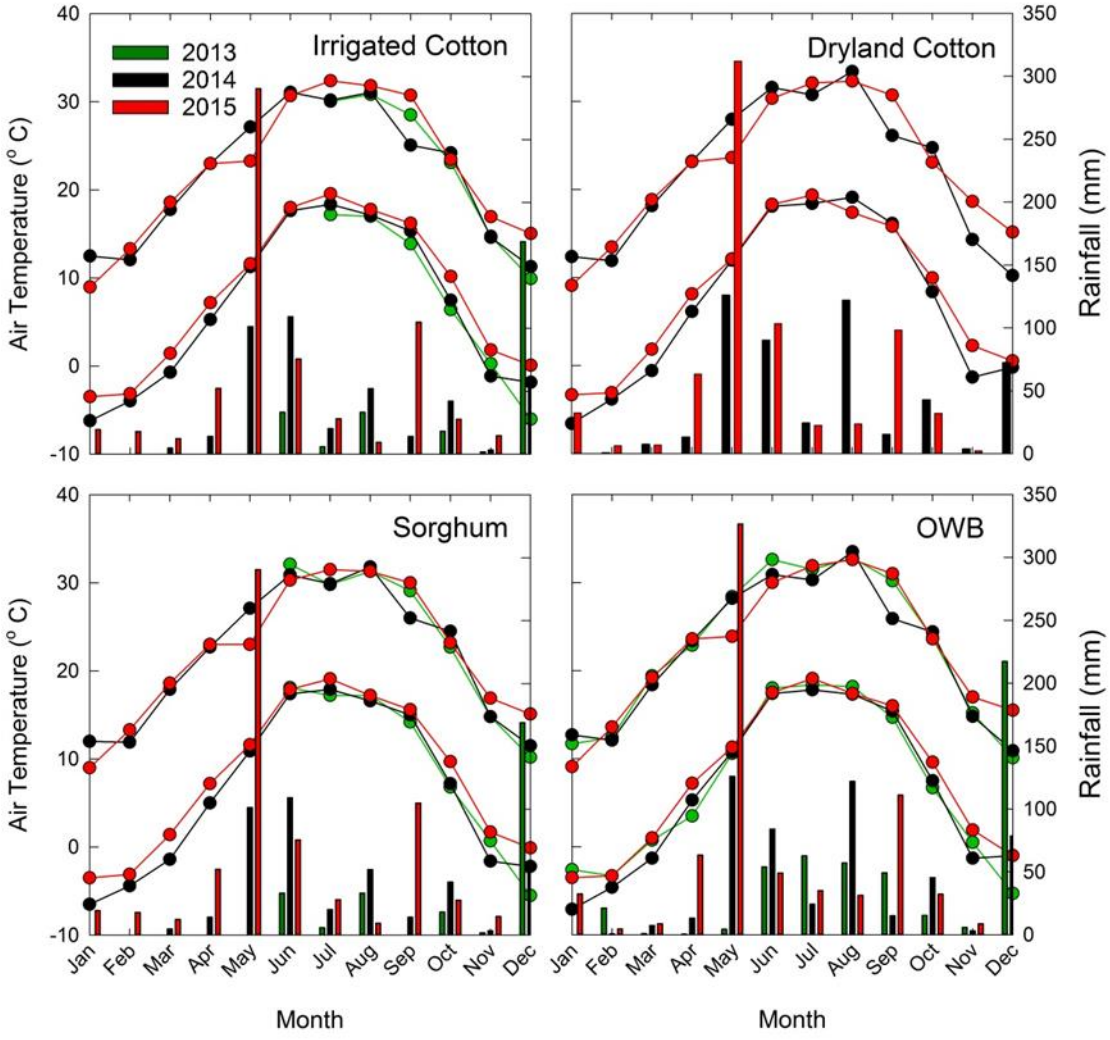


**Figure 4.1. Monthly average maximum and minimum air temperature and rainfall during 2013 (green), 2014 (black) and 2015 (red) in all the research fields. Scattered line plot represent monthly average maximum temperature and minimum temperature, bar plot represents rainfall.**

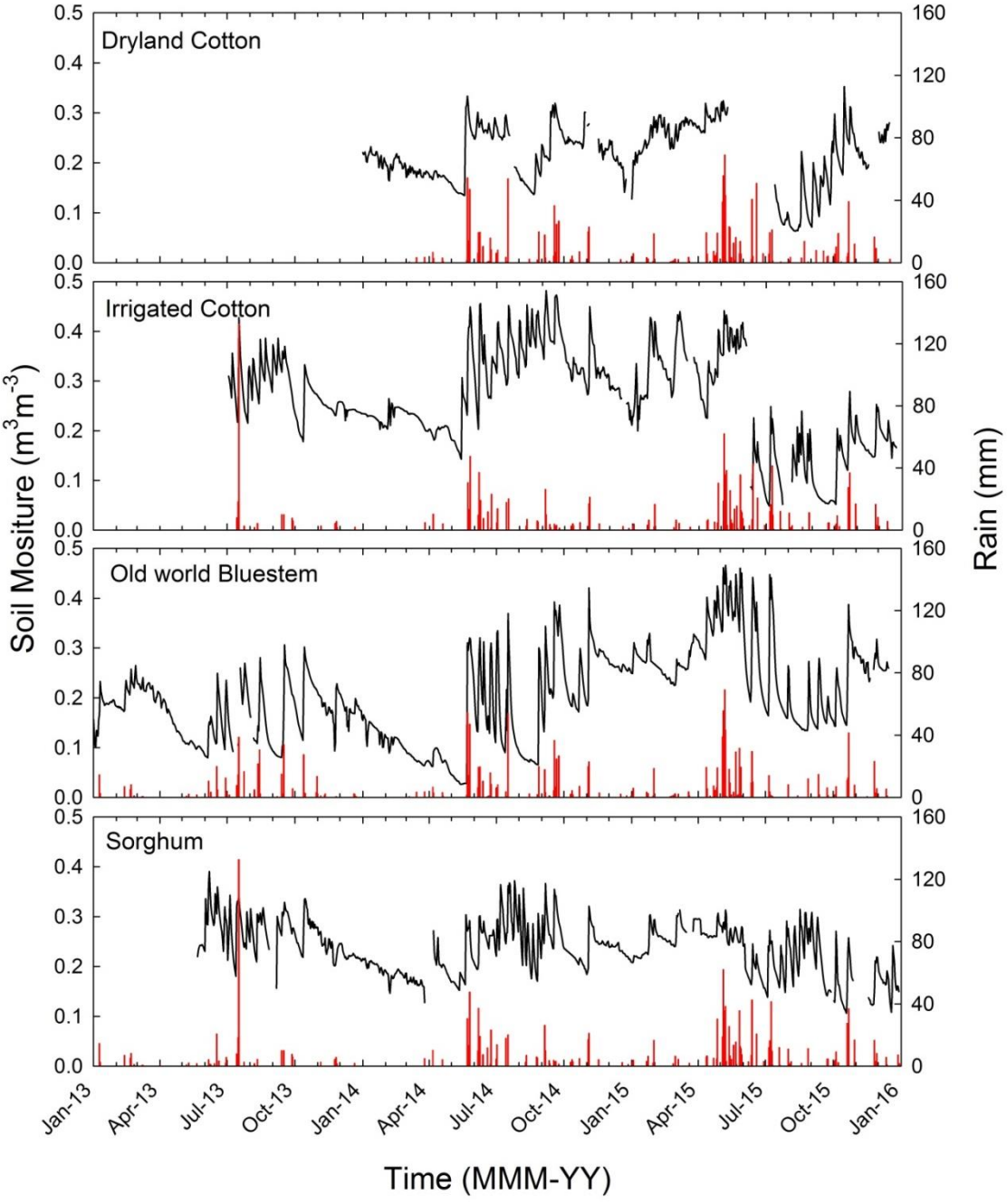


**Figure 4.2. Rainfall and soil moisture at 5 cm depth in all the crops from starting of data collection to end of the study period.**

Figure 4.2 presents soil moisture and rainfall during the entire period of study. Rainfall received during the study period was greater than long term (2002-2012) average of 470 mm measured from mesonet station in Plainview. Total annual rainfall received in dryland cotton field and OWB was 504, 520 and 812 mm in 2013, 2014 and 2015, respectively (Fig. 4.2). Annual rainfall received in sorghum and irrigated cotton field was about 450 mm in 2013, 520 mm in 2014 and 750 mm in 2015 (Fig. 4.2). Second quarter of 2013 (April-May), first quarter (January-April) of 2014 and third quarter (mid-July to September) of 2015 remained relatively dry. Exceptionally high rainfall was recorded in the area during May (326 mm) of 2015. In fact, 65% of the total annual rainfall in 2015 was received by July first week.

**Biometric Measurements**

Figures 4.3 and 4.4 show phenology in sorghum, OWB, irrigated cotton and dryland cotton. Growing season of OWB was longest among all the crops. Growth of Old world bluestem started in April last week or May first week and most of the grass was yellow by the end of October. Sorghum's growing season was shortest among all the crops during all growing seasons. Sorghum's growing season was 140 days in 2013, 147 days in 2014 and 119 days in long 2015. Sorghum plants emerged 4-5 days after planting of June in 2013, 2014 and 2015. Both irrigated and dryland cotton had second largest growing season, stretching from June to mid-October when crops were sprayed with defoliator. Each individual row crop exhibited consistent growing patterns during all the growing season. Phenological stages of each crop synchronized temporally across

all the growing seasons. Growth patterns of OWB varied across the growing seasons and were largely depending on rainfall.

Old world bluestem exhibited a typical C4 plant response following early season rainfalls in 2014 and 2015. In 2013, the growth of OWB was hampered in June due to dry conditions. Above ground biomass (yellow and green leaves) of OWB increased steadily over the growing season. The portion of yellow leaves declined and green leaves increased until it reached peak before declining towards the end of the season. Maximum AGB was registered in August in 2013 and 2015 and in October in 2014. Share of green biomass was also higher during peak AGB measurements. The site bloomed in 2014, leading to stem elongation and hence accumulating higher biomass values during late season in 2014. In 2015, extended dry conditions from mid-July to Late September declined the AGB. As a result the site did not bloom and was turned yellow by the beginning of October itself. Maximum biomass recorded in OWB was 7.3 tons $ha^{-1}$ on DOY 303 in 2013, 10.2 tons $ha^{-1}$ on DOY 274 in 2014 and 10.3 tons $ha^{-1}$ on DOY 223 in 2015. The portion of green leaves in maximum biomass was 59%, 69% and 74% in 2013, 2014 and 2015, respectively. In addition litter samples were collected from OWB field. Amount of litter was high during early growing season due to accumulation of residue from previous crop. However, amount of litter declined as the growing season progressed before increasing again towards the end of the growing season. Maximum amount of litter was measured early in the season on DOY 210 (DOY 9.6 ton $ha^{-1}$) in 2013, on DOY 155 (5.4 ton $ha^{-1}$) in 2014, on DOY 162 (6.5 ton $ha^{-1}$) in 2015.

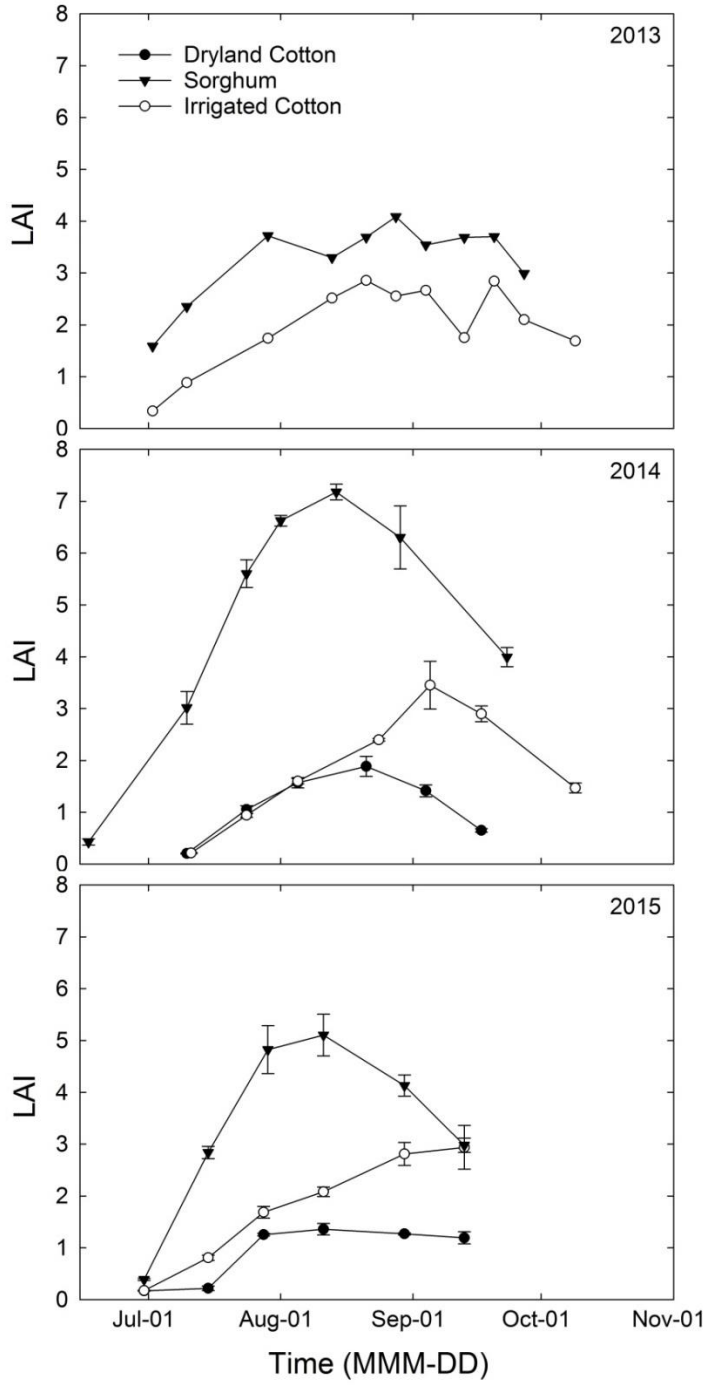


**Figure 4.3. Seasonal evolution of leaf area index (LAI) of the dryland cotton, irrigated cotton, and sorghum. No data was collected in dryland cotton during 2013 as the crop failed due to lack of rainfall. No LAI data was collected in old world bluestem.**

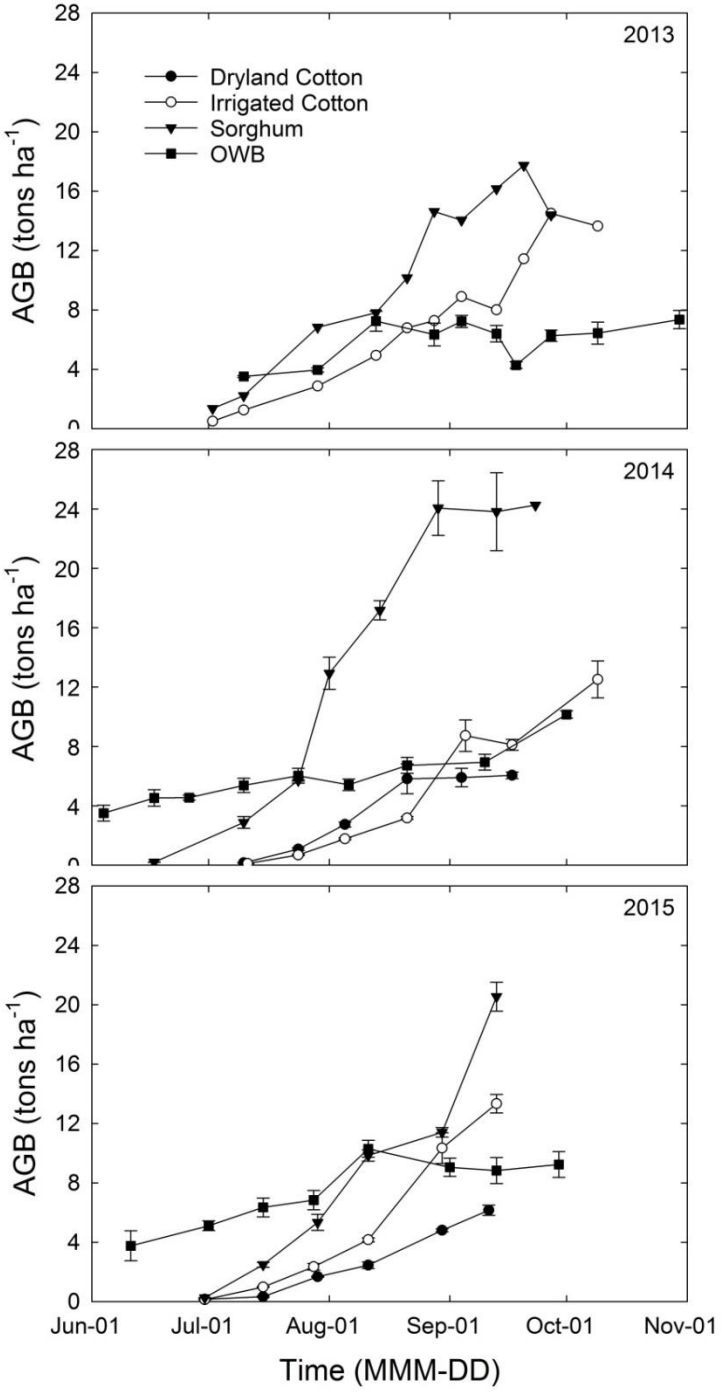


**Figure 4.4. Evolution of above ground biomass (AGB) over the growing season in dryland cotton, sorghum, old world bluestem (OWB). Dryland cotton failed in 2013, therefore no data was presented for this crops in 2013.**

Lowest amount of the litter was recorded at the peak growth period on DOY 240 (4.4 ton $ha^{-1}$), DOY 191 (2.5 ton $ha^{-1}$) in 2014, and DOY 209 (3.9 ton $ha^{-1}$) in 2015. Amount of litter at final sampling of the season in the field was 6.9 ton $ha^{-1}$ (DOY 303) in 2013, 6.3 ton $ha^{-1}$ in 2014 (DOY 317) and 6.8 ton $ha^{-1}$ in 2015 (DOY 272).

Evolution of AGB was consistent in row crops during all growing seasons, though differences in biomass accumulation were evident among the crops. However, the drastic difference between peak AGB were noticed in sorghum across different growing season. As explained in Chapter II, narrower row spacing in 2014 lead to significantly higher AGB during that year in comparison to 2013 and 2015. Peak AGB recorded in sorghum was 18, 21, and 25 tons $ha^{-1}$ in 2013, 2014 and 2015 respectively. Maximum biomass in sorghum was recorded in mid-September at physiological maturity. For cellulosic biofuel production, sorghum biomass is harvested at or before soft dough stage (Saballos, 2008). In our study, sorghum registered peak biomass of 14, 17, and 12 tons $ha^{-1}$ of AGB at soft dough stage by mid-August in 2013, 2014, and 2015, respectively. Similarly, AGB in both dryland and irrigated cotton ascended steadily during both growing seasons. Peak AGB in irrigated cotton was 14.5 tons $ha^{-1}$ on DOY 270 in 2013, 12.5 tons $ha^{-1}$ on DOY 282 in 2014 and 13.3 tons $ha^{-1}$ on DOY 256 in 2015. Dryland cotton registered similar AGB of 6.1 tons $ha^{-1}$ in 2014 and 2015.

In addition to AGB, LAI measurements were taken in row crops. Apparently, sorghum registered consistently higher LAI than both cotton cropping systems across all the growing seasons. Maximum LAI registered in sorghum was 4.1 in 2013, 7.1 in 2014 and 5.1 in 2015. As explained in chapter II narrower spacing and relatively high number

s of tillers lead to significantly higher LAI In 2014 than 2013 and 2015. Peak LAI in sorghum was noticed in August around soft dough stage in 2013 and before soft dough stage in 2014 and 2015. Irrigated cotton registered 2.8 in 2013, 3.1 in 2014 and 2.8 in 2015. Similarly, dryland cotton registered maximum LAI of 1.9 in 2014 and 1.4 in 2015. Irrigated cotton registered maximum LAI in September during 2014 and 2015 growing season. Irrigated cotton registered maximum LAI in August in 2013.

**Energy Balance**

Figure 4.5 represent energy balance of the all the crops during active growing season. An aggregate energy balance closure of each individual crop was measured during active growing season (July-August) across all three seasons. Slope of energy balance in all crops ranged from 0.84 to 0.88, which was within acceptable limits. Energy balance for individual growing season was not very different from aggregated energy balance closure. This confirmed the good quality of data for further analysis.

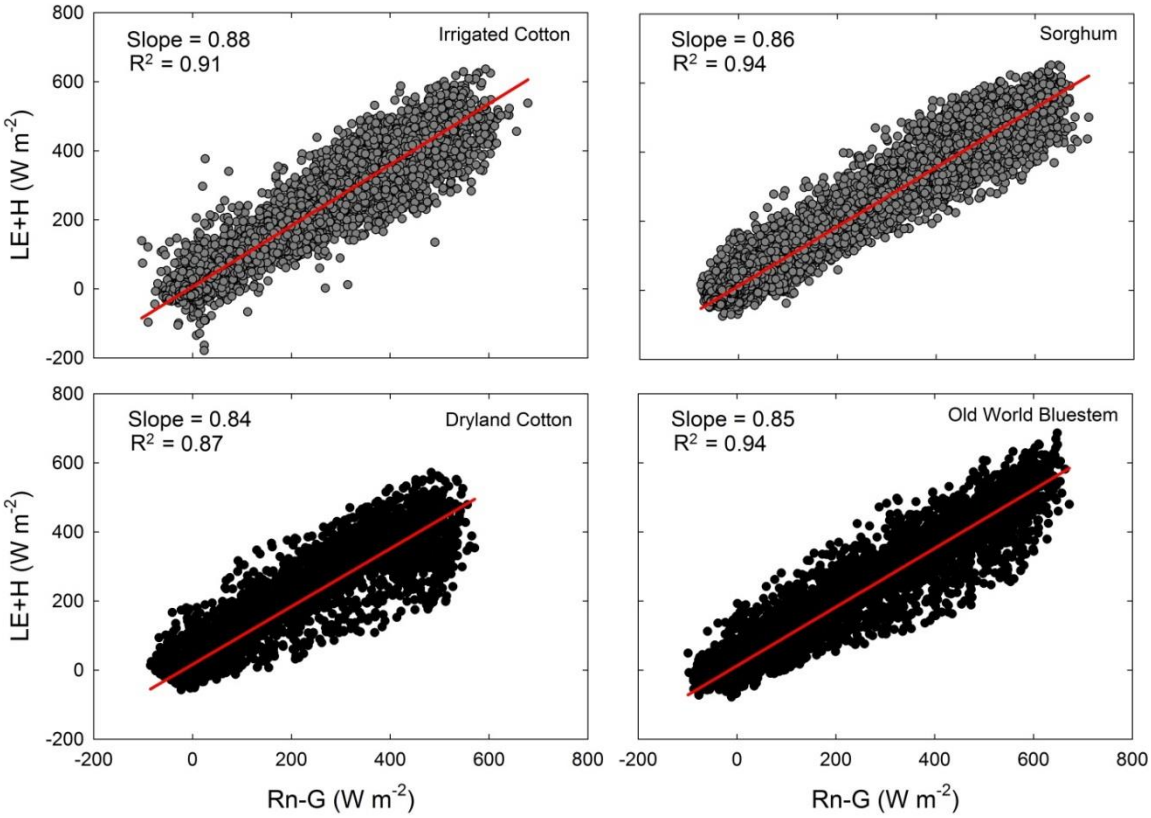


**Figure 4.5. Energy balance closure at different sites during study period. Energy balance components during peak growing season (July-August) were selected from each growing season and plotted together to obtain an aggregated energy balance closure. Each plot consists more than 4000 data points.**

### Seasonal Fluxes of Carbon

Figure 4.6 presents the carbon fluxes data for all the crops throughout the period of study. Inter-seasonal growing patterns of carbon uptake were more or less consistent for each individual row crop, though magnitudes of carbon uptake differed. After emergence, sorghum exhibited rapid growth through June to peak growth in July and August, before declining towards the end of the season. Both irrigated and dryland

cotton were slow at the start, however, growth picked up in July and achieved peak in August. Peak growth was maintained through September before declining towards the end of the season. In contrast, growth patterns of OWB varied each season and were more dependent on rainfall amount and distribution. Old World bluestem grew rapidly from May to July in 2014 and 2015 following early season rainfall. Dry period hampered growth of OWB in June 2013, August 2014 and September 2015.

Seasonal integrals of NEE, GPP and $R_{eco}$ are presented in Table 4.1. Both C4 species registered greater GPP than C3 cotton plants except in 2013. In 2013, irrigated cotton registered higher GPP than OWB, probably due to higher irrigation levels. Cumulative seasonal GPP in sorghum was -1591.9 g C $m^{-2}$ in 2013, -1780.9 g C $m^{-2}$ in 2014, and -1353.7 g C $m^{-2}$, respectively. Irrigated cotton registered -969.7 g C $m^{-2}$, -860.8 g C $m^{-2}$, and -582.1 g C $m^{-2}$ in 2013, 2014, and 2015, respectively. Dryland cotton registered almost similar GPP (-452.8 g C $m^{-2}$ and -450.0 g C $m^{-2}$) during both growing seasons. Old world bluestem registered higher GPP in 2014 (-1140.1 g C $m^{-2}$) and 2015 (-1233.5 g C $m^{-2}$) than 2013 (-877.3 g C $m^{-2}$) mainly due to good early season rainfall in 2014 and 2015, which gave the crop opportunity to grow during peak growing season.

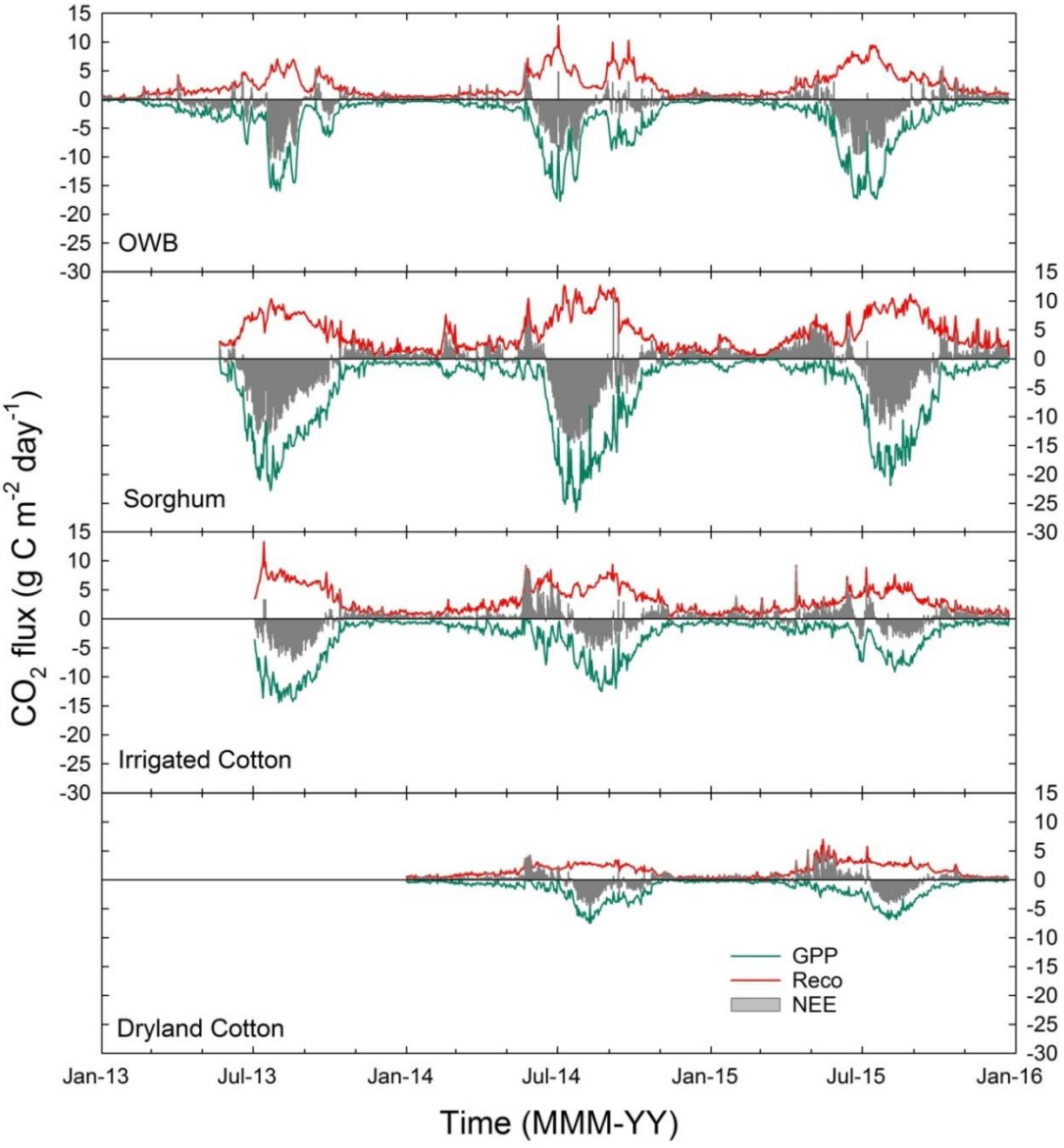


**Figure 4.6. Daily integrated net ecosystem exchange (NEE), gross primary production (GPP) and ecosystem respiration ($R_{eco}$) during the period of study. All three years data was available for old world bluestem (OWB). Data collection from sorghum started from planting in 2013. Data collection in irrigated cotton started after about a month of planting in 2013. Dryland cotton failed in 2013; therefore data from only two seasons is presented. As per sign convention, negative values indicate carbon uptake by the system and positive signs denote carbon release from the system to atmosphere. Line plots represent GPP and $R_{eco}$, bar plot represents NEE.**

**Table 4.1. Seasonal integrals of NEE, GPP and $R_{eco}$ in sorghum, old world bluestem (OWB), irrigated cotton, and dryland cotton. Lower case alphabets alongside mean values represent the statistical difference at p<0.05.**

| | Crop | NEE | GPP | $R_{eco}$ |
|---|---|---|---|---|
| | | | g C $m^{-2}$ | |
| 2013 | | | | |
| | OWB | -314.5 | -877.3 | 562.8 |
| | Sorghum | -710.3 | -1591.9 | 872.1 |
| | Irrigated Cotton | -305.8 | -969.7 | 663.9 |
| | Dryland Cotton | - | - | - |
| 2014 | | | | |
| | OWB | -316.9 | -1140.1 | 823.2 |
| | Sorghum | -665.2 | -1780.9 | 1138.4 |
| | Irrigated Cotton | -81.2 | -860.8 | 766.0 |
| | Dryland Cotton | -116.9 | -452.8 | 327.2 |
| 2015 | | | | |
| | OWB | -373.3 | -1233.5 | 830.3 |
| | Sorghum | -471.5 | -1353.7 | 882.2 |
| | Irrigated Cotton | -21.8 | -582.1 | 560.3 |
| | Dryland Cotton | -90.7 | -450.0 | 359.3 |
| Mean | | | | |
| | OWB | -334.9b | -1114.4b | 638.8b |
| | Sorghum | -615.7a | -1575.5a | 964.2a |
| | Irrigated Cotton | -136.3c | -804.2bc | 663.4b |
| | Dryland Cotton | -104.4c | -457.6c | 315.3c |

**Table 4.2. Mean apparent quantum yield (alpha) and mean $GPP_{max}$ for all the crops. Rectangular hyperbolic relationship was plotted between GPP and PAR for 5-10 selected clear days during peak photosynthetic activity. Lower case alphabets besides values indicate significance level at p<0.05.**

| Crop | Mean Alpha | Mean $GPP_{max}$(umol $m^{-2}$ $s^{-1}$) |
|---|---|---|
| Sorghum | -0.040a | -53.8a |
| OWB | -0.048a | -43.9a |
| Irrigated Cotton | -0.045a | -28.1b |
| Dryland Cotton | -0.030a | -16.1b |

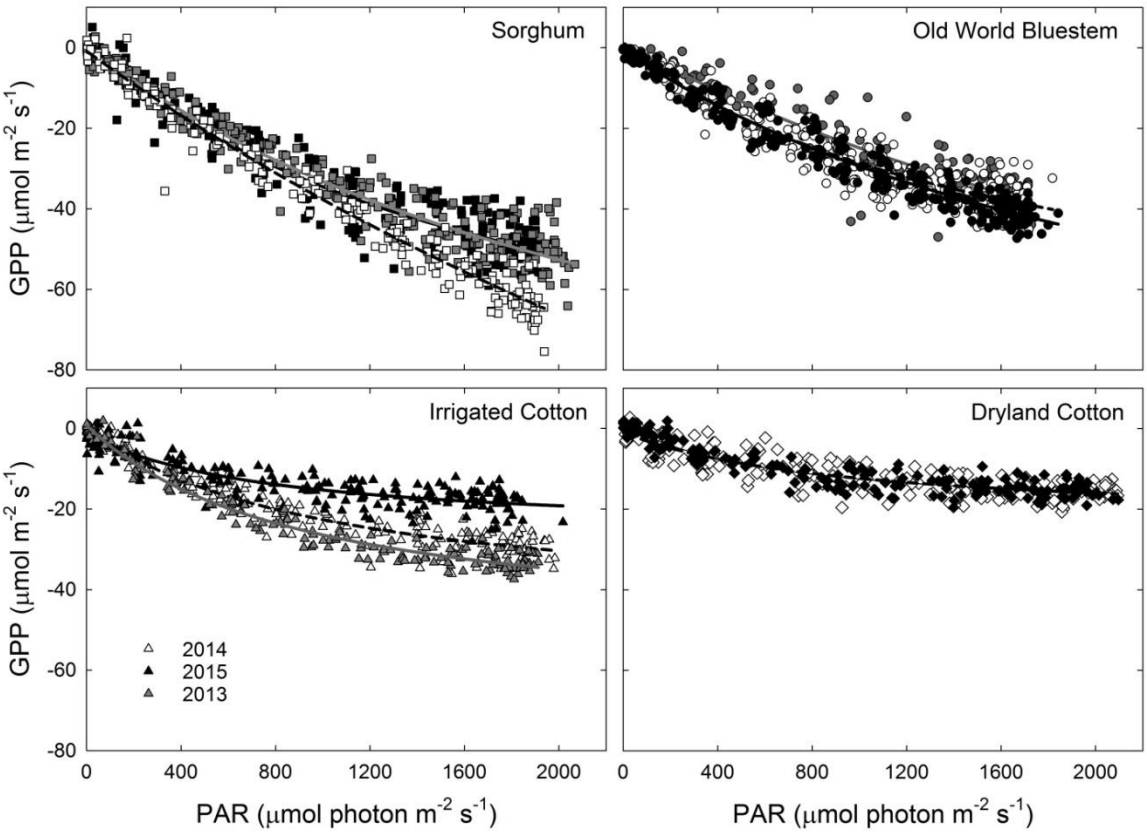


**Figure 4.7. Light response curves of sorghum, old world bluestem (OWB), irrigated cotton and dryland cotton for 2013, 2014 and 2015. Selected clear days during peak photosynthetic activity were chosen. Phenological stage for each individual crop was similar. All the relationships were significant ($p<0.0001$) with $R^2$ ranging from 0.85-0.94.**

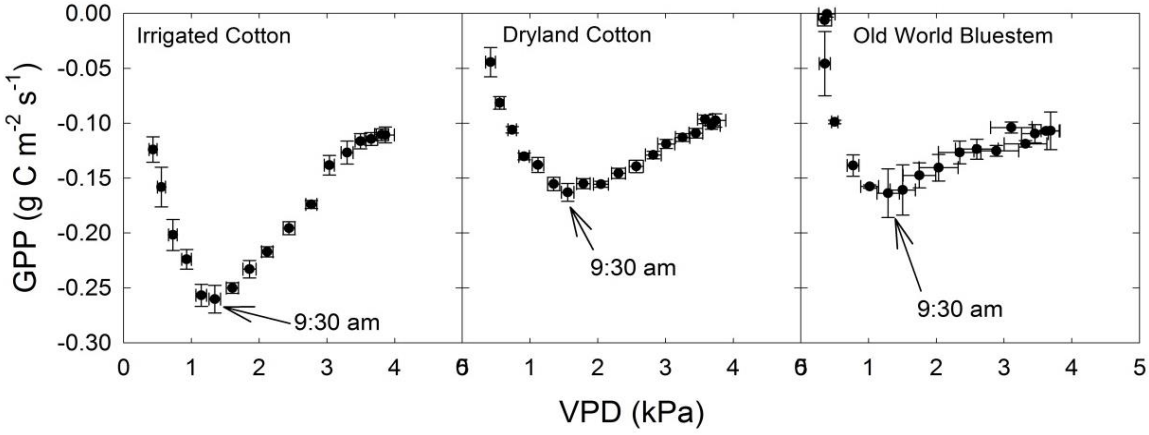


**Figure 4.8. Relationship between gross primary production (GPP) and vapor pressure deficit (VPD) in irrigated cotton, dryland cotton, and old world bluestem during selected days. Clear days were selected when volumetric water content was below 0.20 $m^3$ $m^{-3}$. (DoY 225-228 in 2014 for OWB and DoY 256-260 in 2015 for irrigated and dryland cotton)**

Higher overall GPP in sorghum and OWB could be attributed to higher growth rates. Half-hourly GPP values were plotted against PAR for selected clear days of peak photosynthetic activity from each growing season for all the crops. Phenological stage of individual crop was similar for each selected period during the growing season. Soil VWC was >20 $m^3$ $m^{-3}$ for each crop. Gross primary production was strongly depending upon PAR for all the crops during all growing seasons with $R^2$ ranging from 0.85 to 0.94 (Fig. 4.7). Table 4.2 shows the mean $GPP_{max}$ and apparent quantum yield values for each crop. Although mean apparent quantum yield did not differ among the crops, $GPP_{max}$ in C4 crops was significantly higher than C3 crops ($p<0.05$). The reason for this could be inherited physiological advantages of C4 plants over the C3 plants. In general, C4 plants have higher carbon uptake capacity due to reduced photorespiration in comparison to C3

plants. Overall, both C4 species assimilated significantly high $GPP_{max}$ than C3 cotton ($p<0.05$). Maximum GPP ($GPP_{max}$) was not statistically different among dryland and irrigated conditions ($p<0.05$).

In terms of NEE, all the fields were net carbon sinks during growing season (Fig. 4.6). However, the fields remained a net source of carbon during early growing season, despite initiation of growth. Net ecosystem exchange (carbon uptake) was maximum in sorghum, despite shorter growing season than other crops. Irrigated cotton registered maximum growing season carbon uptake (NEE) during 2013 growing season probably due to greater irrigation during that year. Interestingly, dryland cotton was stronger carbon sink than irrigated cotton in both 2014 and 2015 years, despite higher GPP in irrigated cotton. Seasonal NEE for sorghum was -710.3 g C $m^{-2}$ in 2013, -665.2 g C $m^{-2}$ in 2014, and -471.5 g C $m^{-2}$ in 2015. Similarly, OWB registered NEE of -314.5 g C $m^{-2}$ in 2013, -316.9 g C $m^{-2}$ in 2014, -373.3 g C $m^{-2}$ in 2015. Net carbon uptake in irrigated cotton was -305.8 g C $m^{-2}$, -81.2 g C $m^{-2}$, and -21.8 g C $m^{-2}$ in 2013, 2014 and 2015, respectively.

Lower NEE in sorghum in 2014 despite greater GPP, could be due to higher $R_{eco}$ during growing season in that year. In sorghum, higher proportion of $R_{eco}$ to GPP in 2014 (63%) and 2015 (65%) lead to lower NEE in 2014 than 2013. In fact, $R_{eco}$ registered higher proportion of GPP in all crops during 2014 and 2015. The reason for this could be higher early growing season $R_{eco}$ in all the fields due to heterotrophic respiration, following early season rainfall events in 2014 and 2015. Precipitation enhances release of carbon from soil as the water percolating in soil tends to flush out

the $CO_2$ from soil as well as increases microbial activity (Franzluebbers 2000, Rochette et al., 1991, Talmon et al., 2010, Xu et al., 2004; Huxman et al., 2004). Lee et al, (2010) reported significantly high $CO_2$ flux from a deciduous broad leaf forest on rainy days as compared to non-rainy days. Harper et al., (2005) reported that the amount and timing of rainfall events influenced the soil $CO_2$ fluxes in the grassland.

**Seasonal Variation in Carbon Fluxes**

Seasonal carbon flux trends in sorghum were more or less similar during different growing seasons, whereas carbon fluxes in OWB varied with growing seasons. Therefore, seasonal carbon uptake trends of sorghum will not be discussed in this section. Influence of rainfall amount and its distribution was more evident in OWB than dryland cotton. Considerable drop in carbon uptake of OWB were noticed during dry months of the growing season. Similar drops were observed in irrigated and dryland cotton during September 2015. We plotted GPP for selected clear days during dry period observed in OWB, dryland cotton and irrigated cotton for both years (Fig. 4.8). Phenological stage of each crop was similar during each selected period. Gross primary production increased initially during early morning hours reaching a maximum at 9:30 am, before declining as the day progressed. Wagle et al. (2014) reported similar observation in sorghum and switchgrass during dry period. The authors concluded that rising temperatures in the early morning hours increased RuBISCO activity, which resulted in rapid increase of $CO_2$ assimilation in the early morning hours at lower VPD levels. The authors further concluded that decline in carbon uptake with rising VPD in after noon hours could be explained with stomatal closure due to increasing water stress.

Vapor pressure deficit is a function of air temperature, therefore similar effects were observed with rising air temperature in the afternoon hours of the same period (data not shown). Stomatal closure is coupled with dilution of $CO_2$ concentration at site of photosynthesis at high temperatures, which enhances RuBISCO reactivity with $O_2$, resulting in enhanced photorespiration especially in C3 plants. This explains the observed decline in carbon uptake during afternoon hours in our study during dry conditions. Despite abiotic limitations of the region to carbon uptake, all the cropping systems were net carbon sinks at seasonal scale.

**Annual Fluxes of Carbon**

**Table 4.3. Annual net ecosystem exchange (NEE) of the irrigated cotton, sorghum, dryland cotton, and old world bluestem.**

| Year | OWB | Sorghum | Irrigated Cotton | Dryland Cotton |
|---|---|---|---|---|
| | | g C $m^{-2}$ | | |
| 2013 | -301.9 | -619.3* | -254.3* | |
| 2014 | -265.6 | -444.8 | 101.3 | -19.4 |
| 2015 | -287.2 | -51.4 | 123.8 | 56.9 |

*data from planting to December was available.

Table 4.3 shows the annual carbon budget of all the crops during the study period. At annual scale both potential bioenergy crops were net sink of carbon, whereas irrigated cotton acted as carbon source to the atmosphere. Dryland cotton on the other hand, was a net sink of carbon during 2014 annual cycle, whereas the field was a net source of carbon in 2015. Large variation was observed in annual sinking capacity of

sorghum. The source sink behavior of dryland cotton field could be attributed to greater $R_{eco}$ in early non-growing season in 2015 than in 2014. In fact, sorghum and OWB also registered higher non-growing season $R_{eco}$ in 2015 than in 2014. We plotted weekly average nighttime $R_{eco}$ with nighttime $T_{soil}$ during early non-growing season (January-April) in these three crops (Fig. 4.9). Temperature sensitivity ($Q_{10}$) value in dryland cotton was 3.0 in 2015 in comparison to 1.8 in 2014. Similarly, $Q_{10}$ value for non-growing season in OWB was 2.6 in 2013, 2.2 in 2014, and 4.3 in 2015. Temperature sensitivity ($Q_{10}$) value for non-growing season was 3.3 in 2015 and 1.7 in 2014 in sorghum. Microbial activity increases with increasing soil temperature (Flanagan, 2005). However, several researches have reported decline in microbial activity under dry conditions (Skopp et al., 1990; Davidson et al., 1998; Rajan et al., 2013; Suyker and Verma, 2004). The non-growing season of 2014 was relatively drier than 2015, which explains higher $R_{eco}$ during non-growing season of 2015. It should also be noticed that part of the reason for lower net carbon balance of sorghum in 2015 could be attributed to lower seasonal net carbon uptake in 2015, due to shorter growing season.

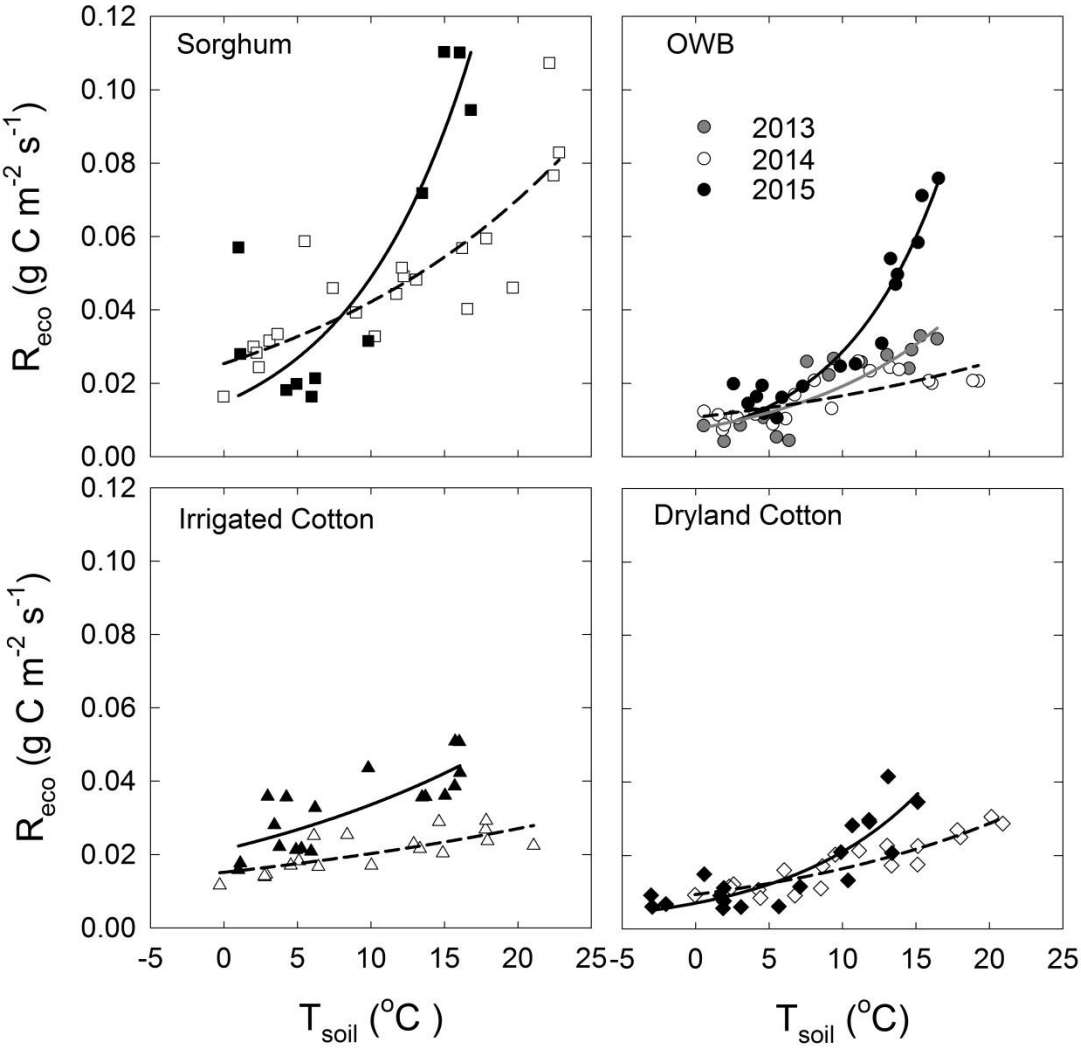


**Figure 4.9: Relationship between average weekly nighttime ecosystem respiration ($R_{eco}$) and nighttime temperature ($T_{soil}$) for sorghum, old world bluestem (OWB), irrigated cotton and dryland cotton during non-growing season January-April in OWB and January-May in row crops. Only original data was used. All relationships were significant at $p<0.0001$ ($R^2$= ranged from 0.57-0.93).**

Irrigated cotton on the other hand, registered higher $R_{eco}$ in 2014 (312 g C $m^{-2}$) than in 2015 (268 g C $m^{-2}$) (Table 4.1). In our research, irrigated cotton was only field to be tilled following harvest of the crop. Tillage has been widely associated with enhanced

microbial respiration and release of $CO_2$ from soil. Tillage mixes the plant residue with soil, thereby increasing the surface area of residue in contact with soil (Lal, 2004). Soil moisture levels in 2014 were higher as they were in 2015 non-growing season. Temperature sensitivity of irrigated cotton during non-growing season was close to 1.3 in 2014 and 1.6 in 2015. Seasonal NEE in 2013 was greater than the other two years, despite almost similar AGB. This suggests that greater amount of carbon was allocated to below ground biomass in 2013, which may have added to the $R_{eco}$ through decomposition during 2014 non-growing season following tillage. Lower carbon uptake and proportionately higher $R_{eco}$ (96% of GPP in 2015 to 90% in 2014) during growing season in 2015 could have been responsible for lower NEE in that year. Overall, two complete year (2014 and 2015) integrals of all the row cropping systems yielded a net carbon sinking of -496.2 g C $m^{-2}$ in sorghum, 225.2 g C $m^{-2}$ in irrigated cotton, and 37.4 g C $m^{-2}$ in dryland cotton. On the other hand, OWB accumulated -854.7 g C $m^{-2}$ in three complete years and -552.8 g C $m^{-2}$ in last two complete years.

Clearly, the annual productivity was higher in bioenergy systems than conventional cotton cropping systems. Inter-annual variability in net carbon uptake was largely depending upon $R_{eco}$ during non-growing season and carbon uptake during growing season. However, the susceptibility of the region to periodic droughts will determine the fate of rainfed OWB as a bioenergy crops. Previous research by Rajan et al. (2013) on OWB site has shown transitioning of the site from net sink in a good rainfall year to a source in a dry year. As mentioned in previous chapter, seasonal NEE

of OWB in our study matches well with those of rainfed sorghum reported by Wagle et al. (2016).

Recall that, poor carbon returns from continuous cotton cropping in Southern high plains have marginalized the soils by depleting soil organic carbon (Acosta-Martinez et al., 2010). In our study, the biomass was never removed from OWB and about 12 inch long stock was left in sorghum field for cattle grazing. Removal of biomass for biofuel production leads to nutrient removal from soil and leaves poor carbon return to soil (Propheter and Staggenborg, 2010). This is important, as plant residue needed to maintain or enhance soil organic carbon could be a constraint for long-term sustainability of bioenergy production systems (Wilhelm et al., 2007; Powers et al., 2011). Propheter and Staggenborg (2010) reported greater nutrient removal by the annual crops (including sorghum *bmr* cultivar) in comparison to switcgrass and *miscanthus*. However, this study was conducted during establishment phase of perennial crops, when their yields are usually lower than annual crops. Similarly, Blanco-Canqui and Lal, (2008) reported net nutrient loss in silt loam soils when all the corn stover was removed from the field, whereas clay loam soils remained unaffected. Cowie et al. (2006) estimated that soil organic carbon losses are likely to happen in soils with high carbon concentration and soil with low carbon concentration are likely to accrue carbon over time. Soil organic carbon in our study was less than 1% in all the fields (data not shown). Powers et al. (2011) using modelling approach concluded that herbaceous crops such as switchgrass could be beneficial for soil and water quality perspective in comparison to traditional corn-soybean cropping systems depending under tillage

practices in US corn belt. Cotton et al. (2013) reported increased level of soil organic carbon under sorghum cropping in high plains soils even after total removal of AGB due to extensive root system. This suggests that marginalized soils of the Southern High Plains will benefit from land use change induced by bioenergy cropping systems. Therefore, bioenergy cropping systems especially perennial cropping systems may prove sustainable in the long term in terms of soil quality in the Southern High Plains. However, threshold levels for biomass removal must be optimized in order increase or maintain the displaced atmospheric carbon levels in the system.

## CONCLUSION

On-site carbon balance of two potential bioenergy crops, sorghum and OWB were compared with conventional cotton cropping system at seasonal and annual scale in the Southern high Plains. We found that both C4 bioenergy crops were robust carbon sinks at seasonal scale in comparison to cotton cropping systems. In fact, seasonal carbon uptake in sorghum was greater than OWB. Seasonal carbon uptake in sorghum was largely affected by growing season length and phenology. However, when calculated on annual scale sorghum exhibited greater variation in net carbon capacity while OWB remained stable. Non-growing seasonal $R_{eco}$ played major role in annual carbon budget of both bioenergy crops. Wet winters in 2015 led to higher carbon release into the atmosphere, thereby declining net carbon budget in sorghum. Rainfall distribution was major controlling factor in growth of OWB. Cotton cropping systems remained net carbon source of the carbon for combined 2014 and 2015 annual cycles. Our findings suggest that a shift from conventional cotton cropping systems to bioenergy

crops will lead to greater on-site carbon assimilation in the Southern Great Plains. However, retention of on-site carbon balance will largely depend upon biomass removal, environmental conditions and agronomic management practices. The Southern High Plains is susceptible to periodic droughts and is facing water crisis due to declining water table in Ogallala aquifer. Therefore, sustainability of these bioenergy cropping systems will largely depend upon the future climatic and irrigation scenarios. We believe that higher carbon uptake in sorghum in our study was due to irrigation. As such, we anticipate a decline in carbon uptake capacity of sorghum under dryland conditions. Therefore, more research is required to assess carbon capacity of sorghum under dryland conditions to assess the long-term sustainability of these systems under water stressed scenario in future.

# CHAPTER V

# IMPLICATIONS OF BIOENERGY CROPS INDUCED LAND USE CHANGE ON ENERGY BALANCE AND EVAPOTRANSPIRATION IN THE SOUHTERN GREAT PLAINS

## INTRODUCTION

Current legislative and regulatory mandates aiming at reducing United States' dependence on foreign oil imports has driven the rising bioenergy crops production in the United States. According to US Energy Independence and Security Act of 2007, a targeted 36 billion gallons of renewable fuel (biofuel) are to be produced by 2022. About 80 billion liters of the total amount will be second generation biofuels, produced from specific biomass crops. By 2016, about 90 billion liters of renewable fuel was produced and a target of 95 billion liters has been set for 2017 (RFS, 2017; https://www.epa.gov/renewable-fuel-standard-program/proposed-renewable-fuel-standards-2017-and-biomass-based-diesel *accessed February 9, 2017*). However, in both years contribution of first generation biofuels has been about 75% of the total renewable fuels. While the major first generation biofuel crops i.e. corn and soybean production as bioenergy crops has rapidly increased in the US corn-belt region (Wright and Wimberly, 2013), there still exists a large gap for specific biomass crops to fill, in order to meet the target for second generation biofuels. As a result, increase in production area of specific biomass crops for second-generation biofuel production is anticipated in future.

Half of the total second generation biofuels are proposed to be produced in the Southeast United States, including the Southern Great Plains (USDA, 2010). The Southern Great Plains is a semi-arid region which is susceptible to periodic droughts. Therefore, agriculture in the Southern Great Plains largely depends upon the water extracted from the Ogallala Aquifer. Infact, 95% of the water extracted from the aquifer is used for irrigation, which has depressed the water table in the Ogallala Aquifer. Introduction to cotton cultivation and central pivot irrigation system as a strategy (Colaizzi et al., 2009) to reduce water consumption in the Southern Great Plains has been successful, as the region produces 20-25% of total cotton production in the United States (Allen et al., 2008). However, with declining Ogallala Aquifer the area is already witnessing a steady shift from irrigated cotton to dryland cotton. Other major crops of the region include, sorghum, corn, soybean and wheat. A large scale production of the bioenergy crops in the region may induce a significant land conversion from conventional cotton cropping system to bioenergy cropping systems.

Increasing land conversion to bioenergy crops in the world has already shifted the current scientific research interests towards sustainability of bioenergy cropping systems. Land required to meet the large scale production of bioenergy crops will come from existing croplands, marginal lands, grasslands or retired croplands mainly CRP lands, inducing land use change in many areas (Fargione et al., 2009; Gelfand et al., 2013; Wright and Wimberly, 2013). Therefore, large scale production of bioenergy crops will compete with food and fiber crops not only for land but also for water and other input resources (de Fraiture et al., 2008). This holds true to the Southern Great

Plains as well, where a significant competition between bioenergy crops and cotton cropping systems for land and water is anticipated in future. However, effects of large scale land conversion to bioenergy crops on ecosystem services including carbon, water and energy balance at ecosystem scale have not been addressed adequately and should not be neglected in implementation of production policy (Robertson et al., 2011; Vanloocke et al., 2012).

Land use change can have major implications on environment as change in vegetation properties can significantly affect the carbon, water and energy budget of a region by modifying albedo and energy balance (Pielke et al., 2002; Keuppers et al., 2007; Twine et al., 2004). Pielke et al. (1998) concluded that land cover is equally important as anthropogenic activity for earth's climate as former can significantly influence weather and climate of a region. Several studies have reported impact of vegetation type on groundwater recharge, water quality, and evapotranspiration (Sesmero, 2014; Humphreys et al., 2003; Delucchi, 2010; Green et al., 2011). In general, environmental implications of conventional annual bioenergy crops are similar to farm crops, but may differ from perennial crops (Fraiture and Berndes, 2009; Abraha et al., 2016). For example, groundwater recharge from the perennial crops is usually lower than annual crops due to greater cumulative ET because of longer growing season (Schilling, 2008; Trost, 2010; Smith et al., 2013). Perennial crops on the other hand, can provide ecosystem services in terms of improved soil health, reduced soil erosion, less agronomic operations, reduced solute leaching to groundwater and improved wildlife habitat (Trost, 2010).

The objective of this research was to assess and compare the water and energy balance dynamics of an annual and a perennial bioenergy crop with the conventional cotton cropping systems in the Southern High Plains. For this study, sorghum was the potential bioenergy crop, which has better potential for established bioenergy cropping systems over corn due to its lower water and nutrient requirements (Rooney, 2007). The perennial bioenergy crop for this study was Old World Bluestem (OWB). Old World bluestem is a resilient drought resistant bunch grass with well-established cropping systems, have potential to emerge as popular bioenergy cropping systems in the Southern High Plains. In addition, most of the CRP lands in Texas have been planted with OWB (Li et al., 2017). We compared sorghum and OWB with conventional cropping systems of irrigated and dryland cotton using eddy covariance method. Data from this study will be useful to parameterization of land surface models and remote sensing models to estimate evapotranspiration and energy balance at regional scale.

## MATERIALS AND METHODS

### Study Site

This study was conducted in four different farmers' fields fitted with central pivot irrigation systems in the Texas High Plains region. The high biomass forage sorghum field, managed for commercial seed production, was located approximately 3.5 miles northeast of Plainview, TX (34°12'34.70'' N and 101°37'50.85'' W, 1100 m elevation). The cultivar planted was Surpass XL *bmr* (brown midrib). Sorghum was planted on one half of the field and the remaining half was planted with cotton (*Gossypium hirsutum* L.). The farmer practiced crop rotation between these crops on

both halves of the field. Management practices prior to planting sorghum included mowing down of cotton stubbles after harvesting previous cotton crop followed by tillage in spring and before planting the crop. Total area planted with sorghum each time was about 25 ha. The crop was planted on 20 May in 2013 and 2014 at a seeding rate of 4.9 kg $ha^{-1}$. Heavy rains in late May during 2015 delayed planting, thus the crop was planted on June 4 in 2015 at the same seeding rate. The row spacing in 2013 and 2015 was 40 inches and 20 inches in 2014. Urea was broadcasted in the field in spring before planting at a rate of 150 kg N $ha^{-1}$. In addition, 30 kg $P_2O_5$ $ha^{-1}$ was also applied prior to planting. The field was irrigated with low elevation application center-pivot irrigation system during the crop growth period. For first 40 days the field was supplied with 0.75 inch and for rest of the season it was supplied with 1.5 inch water during each irrigation event. The field was supplied with about 400 mm of water through irrigation in 2013, about 400 mm in 2014 and about 270 mm in 2015. Also, the field was cultivated in between the plant rows to kill weeds twice in June every year when the crop was still small. The field was harvested for seed on 8 October in 2013, on 14 October in 2014, and on October 1 in 2015. The growing season was 140, 147, and 119 days long for 2013, 2014, and 2015, respectively. Equipment availability and late season rainfall affected the timings of harvest. The field remained fallow post-harvest in winter and spring. The farmer let the remaining stalk grazed by cattle in March 2014 and in January 2015. A fence was put around the tower during the presence of cattle in the field. Since the crop was grown in rotation with cotton, the new crop was planted on other half of the field where cotton was produced in previous season. The major soil mapping unit at the

study site is Pullman clay loam (a fine, mixed, superactive, thermic Torrertic Paleustoll) with 0 to 1% slope.

The perennial grassland was located about 5 km (34$^{o}$ 08'47" N, 101$^{o}$25'48" W) west of Lockney, TX and was established in 2007. The pasture was seeded with WW-B Dahl Old World Bluestem (OWB) (*Bothriochloa bladhii* L.) at the seeding rate of 2.8 Kg seed ha$^{-1}$. "WW-B. Dahl" OWB was released in 1994 jointly by USDA-ARS, USDA-SCS, Texas Tech University, and the Texas Agricultural Experiment Station originally from a selection made in India. It is a bunchgrass with an upright growth habit and has better drought tolerance and water use efficiency than conventional cropping systems in the Southern Great Plains. Total area of the site is about 42 ha. Until 2011 the field was used for grazing by the cattle or for seed production. This field was equipped with a center pivot irrigation system; however, no irrigation, nutrient supply or grazing operation was conducted during the study period (2013-2015). The growing season for the crop roughly ranged from May to October. Peak growing season occurred from June to July depending upon precipitation. The grass remained in vegetative state for most part of the growing season and bloomed in late September/early October. The field was harvested for seed on November 14, 2014. No seed harvesting was done in 2013 and 2015. The field was never harvested for hay. Major soil mapping unit in the field was Pullman clay loam with 0-1% slope.

The irrigated cotton field was located adjacent to sorghum field about 4 km north-east of Plainview in Hale county. In 2013, Cotton was planted in first week of June. First planting of cotton on May 30 was failed and cotton was replanted on June 9.

In 2015, cotton was planted on June 2. Cotton variety planted was Fibermax 2322 at a seeding rate of 40,000 seeds per acre during all years of study. Cotton was applied with 100 Kg $ha^{-1}$ of nitrogen (N) and 35 kg $ha^{-1}$ of $P_2O_5$ before planting. Total area of cotton planted was about 60 acres. Row spacing was 1 m. The field was irrigated using a center-pivot irrigation system. Cotton was sprayed with defoliator (Ginstar) during last week of October. Cotton was harvested on November 7-8 each year of study. Cotton stubbles were mowed down to about 4 inch height after harvest. Irrigated cotton in this study was rotated with sorghum.

Dryland Cotton field was located about 3 km north of Lockney, TX. Dryland was planted on June 1 in 2013, 2014 and 2015. The crop failed in 2013 and farmer ploughed the field to claim crop insurance. In 2015, the farmer decided to plant grain sorghum in the field. As a result, the tower was moved to a nearby dryland cotton field. The size of both fields was about 100 acres. The crop was planted with variety Fibermax 2011 during all years of study. Row spacing was 1 m. Crop was planted at seed rate of 26000 seeds per acre. No fertilizer was applied to the field in 2014 and 2015. The field was sprayed with defoliator (Ginstar) on October 21 in 2014. The field was harvested on November 6. In 2015, the crop was damaged due to hailstorm on July 7 and 8, but the crop resumed growth successfully to complete the life cycle. However, late season rains damaged the cotton bolls and farmer did not harvest the field.

**Eddy Covariance Data Collection**

Carbon dioxide, water vapor/latent heat (LE) and sensible heat (H) fluxes were measured in the fields using eddy covariance systems. While the eddy covariance system

in grassland was established in 2010, the tower in sorghum, irrigated cotton, and dryland cotton was established at planting in 2013. Measurements from irrigated cotton started about a month after planting. All towers were set up in the middle of the fields, with fetch of about 150 m from all directions. An integrated sonic anemometer (Model CSAT-3A, Campbell Scientific) and infra-red gas analyzer (IRGA, Model EC-150, Campbell Scientific) called the IRGASON was used to measure wind velocity and $CO_2$, $H_2O$ vapor concentration, and H in the ambient atmosphere. In grassland the $CO_2$, $H_2O$ vapor concentration was measured using Li-7500 IRGA (LI-COR Biosciences) and wind velocity and sensible heat flux were measured using sonic anemometer sonic anemometer (Model CSAT-3A, Campbell Scientific). The system was installed in middle of each field with fetch of 150 m or more from all directions. These instruments were set up facing south-southwest (in the prevailing wind direction) at a height of about 2.1 m from ground surface. The height of the instrument was adjusted in sorghum field during growing season with increasing crop height to a final height of about 2.6 m from ground. Other environmental variables measured at both sites included air temperature ($T_{air}$) and relative humidity (RH) (HMP50, Campbell Scientific), net radiation (Kipp & Zonen NR-Lite net radiometer), photosynthetically active radiation (PAR) (LI-200SL quantum sensor, LI-COR), solar irradiance (LI-190SB pyranometer, LI-COR), precipitation (TE525 rain gauge, Campbell Scientific), soil temperature ($T_{soil}$) at 4 cm below the surface (TCAV averaging soil thermocouples, Campbell Scientific), and soil volumetric water content at 4 cm below the surface (CS-616 water content reflectometer, Campbell Scientific). Self-calibrating soil heat flux plates (HFPSC-01, Hukseflux,

Campbell Scientific, Logan, UT) were used to measure soil heat flux at 8 cm depth from soil surface. Soil heat storage which is the amount of heat stored in 8 cm soil depth over soil heat flux plates was calculated using the following equation:

$$S = \frac{\Delta T_s C_s d}{t} \qquad [5.1]$$

Where S is the storage term, $\Delta T_s$ is change in surface soil temperature, $d$ is depth of soil in meters above soil heat flux plate, $C_s$ is the heat capacity of moist soil, and $t$ is time in seconds. Heat capacity of soil can be calculated from following equation using bulk density ($\rho_b = 1.3$ gm $cm^{-3}$), volumetric water content ($\theta_v$), density of water ($\rho_w = 1000\ kg\ m^{-3}$), heat capacity of water ($C_w = 4.2\ kJ\ kg^{-1}K^{-1}$), and heat capacity of dry soil ($C_d = 840\ J\ kg^{-1}K^{-1}$):

$$C_s = \rho_b C_d + \theta_v \rho_w C_w \qquad [5.2]$$

Soil heat storage term was calculated using temporal variations in soil temperature and soil moisture in Eq. [5.1] and [5.2]. Soil heat storage term and measured soil heat flux were added to obtain soil heat flux at surface (G).

Infra-red gas analyzer and net radiometer surfaces were cleaned regularly as per manufacturers' guidelines to avoid accumulation of dust. Data from the CSAT3A sonic anemometer and IRGA system were measured at 10-Hz sampling rate using a CR3000 datalogger (Campbell Scientific). All other environmental variables were measured at 5 seconds interval. The datalogger was programmed to calculate and save 30-min average values of all environmental variables. The raw 10-Hz wind velocity and EC150/LI-7500 data were saved for further post-processing and analysis of $CO_2$ and energy fluxes.

**Data Processing and Gap filling**

Data from eddy covariance system was used to calculate half-hourly $CO_2$ and energy fluxes. The flux measured from the eddy covariance tower is the average of the product of the covariance between scalar ($CO_2$, water vapor and temperature) and vector (vertical motions of wind). The high frequency data were analyzed using EddyPro 4.0 software (LI-COR Biosciences, Lincoln, NE). Flux computation requires a series of operations in order to apply corrections to raw data for flux computation. Some of these corrections include spike removal, block averaging, coordinate rotation, spectral corrections for flux losses (Moncrieff et al., 1997), and correction for air density fluctuations (Webb et al., 1980). EddyPro software has built-in functions to apply these corrections and process the eddy covariance data.

Occasional gaps in the flux data occurred during power failure or maintenance were gap filled. In addition, the physically implausible values in the data were also filtered and gap filled. Further, the flux is usually underestimated during low turbulence conditions and therefore, data during low turbulence conditions (when the friction velocity (u*) was <0.10 m $s^{-1}$ (Rajan et al., 2015)) was filtered and gap-filled. In sorghum, the average u* during growing season was 0.31 $ms^{-1}$, 0.33 $ms^{-1}$, and 0.31 $ms^{-1}$ in 2013, 2014, and 2015, respectively. The average u* during growing season in grassland was 0.31 m $s^{-1}$, 0.36 m $s^{-1}$, 0.31 m $s^{-1}$. After screening the data for out of the range and above mentioned filtering criteria, the amount of data which was either missing or did not clear the quality check criteria was about 21%, 8%, and 40% in 2013, 2014, and 2015, respectively. During growing season, 21%, 13 and 3% data was gap-

filled in 2013, 2014, and 2015 respectively. The amount of data to be gap filled in grassland was 32, 16 and 25% of the total data in 2013, 2014, and 2015, respectively.

The CarboEurope and Fluxnet eddy covariance gap-filling on-line tool (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/) was used for gap filling, which is based on the methods similar to those described in Falge et al. (2001) and Reichstein et al. (2005). The data of direct interest such as fluxes is gap filled by averages of ± 7 days windows under similar meteorological conditions when all the meteorological variables are available. The similarity of meteorological conditions is defined when radiation, $T_{air}$ and VPD do not fluctuate beyond threshold values of ±50 W $m^{-2}$, ±2.5 $^{o}$C, and ±0.5 kPa, respectively. This window is expanded to ±14 days, in case similarity in meteorological conditions is not achieved within 7 days window.

Flux partitioning into GPP and $R_{eco}$ were done using empirical model developed from night-time NEE and soil temperature (4 cm) data. Night-time NEE values represent $R_{eco}$, which includes soil and plant respiration. Night time was selected when the global radiation was below 20 W $m^{-2}$ threshold. Daytime $R_{eco}$ was evaluated using an exponential regression model developed between nighttime NEE measurements and corresponding soil temperature ($T_{soil}$) measurements made at the 4-cm depth. The general form of the regression model is:

$$R_{eco} = Ae^{(B*Tsoil)} \qquad [5.3]$$

where A and B are constants evaluated with least squares regression.

Only original measured data was used to parametrize this model. Further, daily $R_{eco}$ and NEE was calculated by integrating daytime and nighttime measurements. Daily gross primary production (GPP) was calculated as:

$$GPP = R_{eco} - NEE \quad [5.4]$$

Ecosystem respiration includes both heterotrophic and autotrophic respiration. The sign convention used was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

**Energy Balance Closure**

Quality of eddy covariance data is very important and can be determined the energy balance closure (Wilson et al., 2002). The energy balance closure at the site was examined by regressing 30-min $R_n$ data against the corresponding sum of LE, H, and G. To examine energy balance closure a linear regression was performed between available energy (Rn-G), and energy fluxes of LE and H. While soil heat storage term was calculated as mentioned above, the canopy storage and energy used for photosynthesis was not calculated for this analysis. Good quality original data for LE and H were used to assess energy balance closure when all the energy balance components were available. Physical and biochemical energy storage terms in the crop canopy layer were assumed to be negligible and thus, were not used in the energy balance closure (Wilson et al., 2002). The difference between $R_n$ and G represents the available energy at the surface. Assuming negligible heat storage within the canopy and net horizontal advection of energy, the energy balance can be described as:

$$R_n - G = LE + H \qquad [5.5]$$

The sign convention used for Rn and G are positive when the flux is downwards and negative when the flux is upward. The sign convention used for LE, H and C fluxes was a positive flux represents flux from the ecosystem to the atmosphere, while a negative flux represents flux from the atmosphere to the ecosystem.

The 30 min LE data was used to calculate ET using the following equation:

$$ET = \frac{LE}{\rho_w \lambda} \qquad [5.6]$$

where, $\rho_w$ density of water (1000 kg $m^{-3}$), and $\lambda$ is the LE of vaporization ($2.5 \times 10^6$ J $kg^{-1}$). Ecosystem water use efficiency (EWUE) at monthly and seasonal scales was calculated by dividing daytime cumulative GPP with daytime cumulative ET at monthly, and seasonal timescales, respectively.

**Biometric Data**

Plant dry biomass weight was measured during the growing season. Sorghum plant samples were taken randomly (3 replications) from the field to measure leaf area index (LAI), dry leaf mass and dry shoot mass. For grasslands, four random plant samples (for green, yellow leaves and litter) were taken from quarter of a meter area. No LAI measurements were done on the grass samples. Plants were stored in an ice chest in the field and leaf area of sorghum was measured (after separating leaves from shoots) using a leaf area meter (Model LI-3100, Licor Biosciences, Lincoln, NE) immediately after they were brought to the laboratory. For grass samples, green and yellow leaves were separated after samples were brought to the lab. After measuring leaf area, leaves

and shoots were stored in paper bags and dried at 65$^{o}$C for one week. Dry mass of shoot and leaves was taken immediately after removing the dried samples out of the oven. Plant density (number of plants per m$^{2}$) and leaf area were used to calculate the LAI.

## RESULTS AND DISCUSSION

### Phenology

Phenological parameters are presented in Figure 4.1 and 4.2 in Chapter IV. Leaf area index and above ground biomass were measured in all the row crops once a significant crop stand was established. Only above ground biomass and litter measurements were made in OWB. Sorghum recorded the maximum LAI among the row crops followed by irrigated cotton and dryland cotton. Maximum LAI ranged from 4.1 in 2013 to 7.1 in 2014 for sorghum, 2.8 in 2013 to 3.1 in 2014 for irrigated cotton and 1.9 in 2014 to 1.4 in 2015 for dryland cotton. Maximum LAI in all crops occurred around mid-August across all growing seasons. On the other hand, maximum aboveground biomass was recorded around physiological maturity of all the crops. Maximum biomass ranged from 18 tons ha$^{-1}$ in 2013 to 25 tons ha$^{-1}$ in 2014 in sorghum, 14.5 tons ha$^{-1}$ in 2013 to 12.5 in tons ha$^{-1}$ in 2015 in irrigated cotton and 6.1 tons ha$^{-1}$ in dryland cotton during both years of study. Maximum aboveground biomass including yellow and green leaves in OWB ranged from 7 to 10 tons ha$^{-1}$. Detailed discussion on phenology and weather are provided in chapter 3.

**Energy Partitioning**

Partitioning of available energy i.e. net radiation in different crops is presented in Fig. 5.1. All three years data was available for OWB (2013-15) and two full (2014 and 2015) year data was available for dryland cotton. Data for irrigated crops was available from their first planting date in 2013 to December 2015. Available energy was mainly dispersed between LE and H. Magnitude of G remained lower across all fields throughout the study period. Sensible heat dominated energy partitioning during non-growing season (November-April) in all fields. Latent heat was greater in magnitude than H in January 2015 following snowfall and rain events.

Old world bluestem had the longest growing season (May-October), followed by cotton (June- mid-October) and sorghum (June-September). Irrigated crops showed consistent growing season behavior in energy partitioning during all growing seasons. Latent heat was the major energy dispersal component during active growing (June-September) season in both irrigated crops followed by sensible heat, and soil heat flux. Early onset of rainfall in 2015 led to shift in energy dispersion from H to LE in both fields in May itself. For irrigated cotton, largest monthly LE was observed in August during all growing seasons. Maximum monthly LE was 177 W $m^{-2}$ in 2013, 132.6 W $m^{-2}$ in 2014 and 119 W $m^{-2}$ in 2015. Maximum monthly H of 80.5 W $m^{-2}$ and 71.5 W $m^{-2}$ were observed in April 2014 and 2015 in irrigated cotton. On the other hand, sorghum recorded largest LE in July of 2013 (141.2 W $m^{-2}$) and 2014 (153.2 W $m^{-2}$) and in August of 2015 (140.6 W $m^{-2}$). Largest magnitude of H for sorghum was observed in May (82.1 W $m^{-2}$) in 2013, March (57.7 W $m^{-2}$) in 2014 and June (67.0 W $m^{-2}$) in 2015.

Among dryland crops, dryland cotton followed similar patterns of energy dispersion as in irrigated row crops. LE dominated H from June-October in 2014, and from May to October in 2015. Sensible heat dominated the energy dispersal for the rest of the season in dryland cotton. Maximum monthly LE in dryland cotton was observed in July (86.0 W $m^{-2}$) in 2014 and in August (95.5 W $m^{-2}$) in 2015. Maximum monthly H was observed in June (76.1 W $m^{-2}$) in 2014 and April (55.6 W $m^{-2}$) in 2015. Infact, magnitude of H was comparable to LE during these months in dryland cotton.

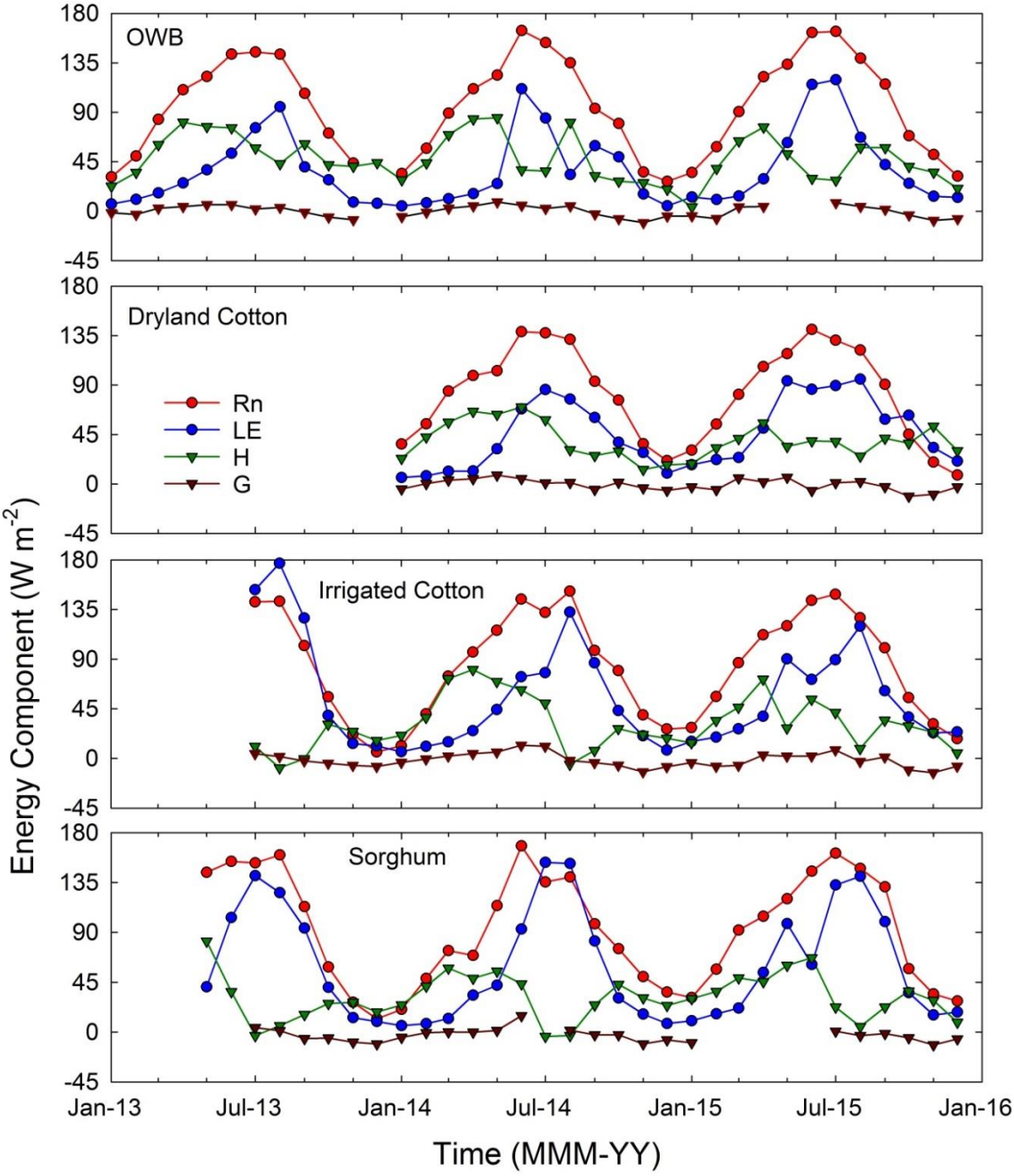


**Figure 5.1. Energy partitioning in net radiation (Rn), latent heat (LE), sensible heat (H) and soil heat flux (G) during the study period in different crop fields. Measurement in sorghum and irrigated cotton started from May and July 2013, respectively. Dryland cotton failed in 2013 and has not been presented in this data.**

In contrast, OWB energy partitioning varied between H and LE during active growing season. Lack of rainfall events kept H the dominant energy component in May and June 2013 in OWB field. Latent heat remained dominant energy component in July and August, before H became the dominant component for the rest of the growing season in 2013. In 2014 growing season, LE remained dominant for June, July, September and October. In 2015 growing season, LE dominated H from May-August, following which H dominated for the rest of the growing season. Maximum monthly LE for OWB was observed in August (95 W $m^{-2}$) in 2013, in June (111.4 W $m^{-2}$) in 2014 and in July (119.7 W $m^{-2}$) 2015. Maximum monthly H in OWB was observed in April in 2013 (81.0 W $m^{-2}$) and 2015 (85.1 W $m^{-2}$) and in May (76.4 W $m^{-2}$) in 2014.

Large portion of energy was partitioned to LE during wet period and to H during dry period in OWB during active growing season. Similar findings were reported by Wagle et al (2014) for rainfed switchgrass during active growing season. Wagle et al. (2014) concluded that energy partitioning was sensitive to both climatic and biological factors. We plotted daily average Bowen ratio (H/LE) against surface soil moisture in OWB for all the growing seasons together (Fig. 5.2). Our results show that energy dispersal among H and LE significantly depended on the soil surface VWC during active growing season (July-September) (Fig. 5.2). These results suggest that the system was actively losing energy in form of LE when the soil VWC was greater than 0.20 $m^3$ $m^{-3}$, and in form of sensible heat once the soil moisture dropped this threshold level. It should be noted that for Pullman clay loam the permanent wilting point is around 0.20 $m^3$ $m^{-3}$ (Howell et al., 2004; Rajan et al., 2014). This finding is in good agreement with those

reported by Rajan et al. (2015) for the same site during a two year study involving drought and wet year, and with those reported by Gu et al. (2006). Latent heat is associated with evapotranspiration, as the water vapor leaving surface carries the amount of energy equivalent to latent heat of vaporization. Irrigated cotton and sorghum showed similar behavior, however the LE dominated for most part of the active growing (July-August) season due to irrigation. Bowen ratio in irrigated cotton was significant function of soil moisture, while sorghum was not. Dryland cotton just like OWB showed similar behavior during active growing season, however it was not significantly related to surface soil moisture.

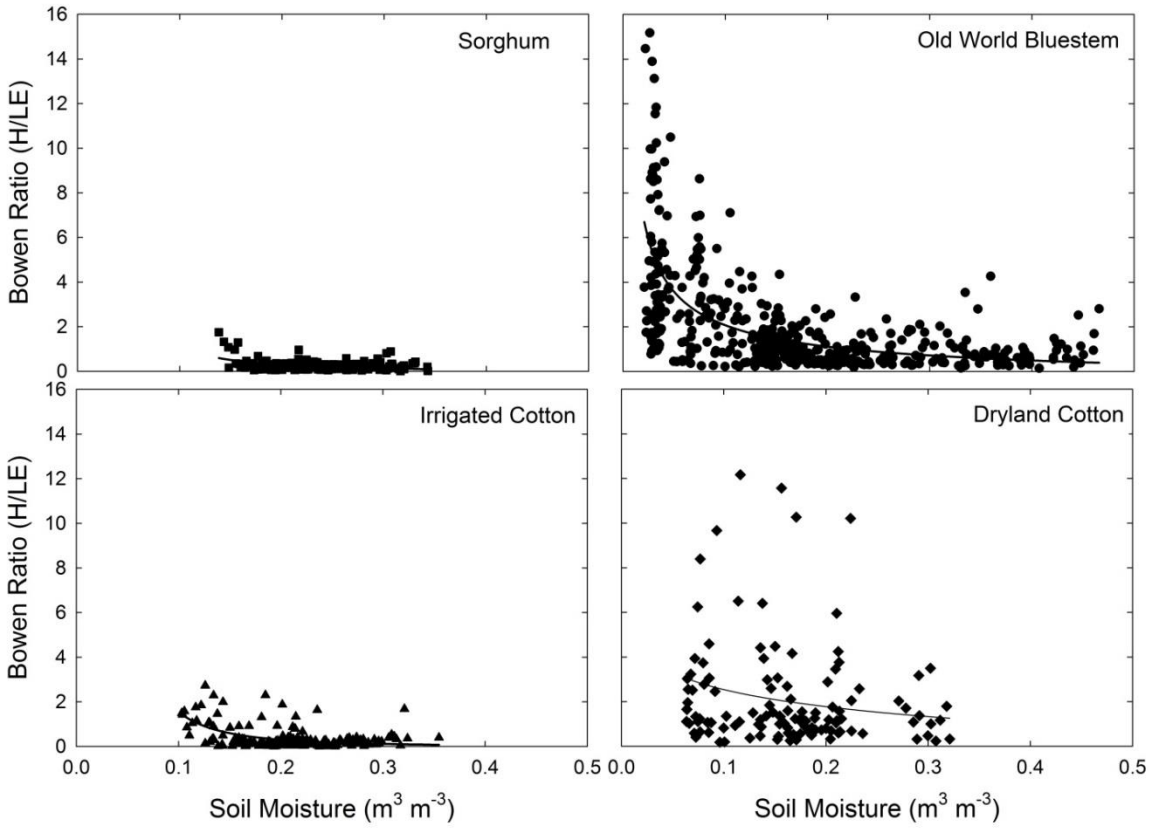


**Figure 5.2. Relationship of daily Bowen ratio with daily average soil moisture (5 cm) content. Daily Bowen ratio from all three active growing seasons (June-August) was plotted together against respective soil moisture. Irrigated Cotton ($R^2$=0.25) and Old World Bluestem ($R^2$=0.41) had significant relationships. Sorghum and Dryland Cotton were not significantly related to soil moisture.**

## Seasonal and Diurnal ET

Figure 5.3 shows the regular seasonal pattern of evapotranspiration in irrigated crops during all growing seasons. Evapotranspiration largely remained small in January and February. Average daily ET during this time (January-February) of all years was similar in sorghum (0.4±0.02 mm, (average ± standard error)), irrigated cotton (0.4±0.02

mm) and dryland cotton (0.5±0.03 mm). Old world bluestem registered slightly less ET (0.3±0.02) during January and February of all years. These ranges of daily ET are consistent with those (0.5 mm $day^{-1}$) reported by Eichelmann et al. (2016) for switchgrass in Canada, Skinner and Adler, (2010) in north-eastern United States, Wagle et al. (2014) in Oklahoma, and Wever et al. (2002) for tall prairie. Similarly, average daily ET from March to May of all years was similar in all the row crop fields (1.3±0.11 mm $day^{-1}$ in dryland cotton, 1.4±0.11 mm $day^{-1}$ in irrigated cotton, and 1.5±0.11 mm $day^{-1}$ in sorghum) and slightly low (0.9±0.05 mm $day^{-1}$) in OWB. March onwards ET started rising with increasing temperatures, until reached a temporary peak in May 2014 and 2015 following early season rainfalls. Lower ET in OWB during non-growing season could be attributed to litter accumulation over surface, which may have acted as insulation to water vapors escaping to atmosphere. Many studies under no-till management have reported similar behavior of plant residue on ET (Barbieri et al., 2012).

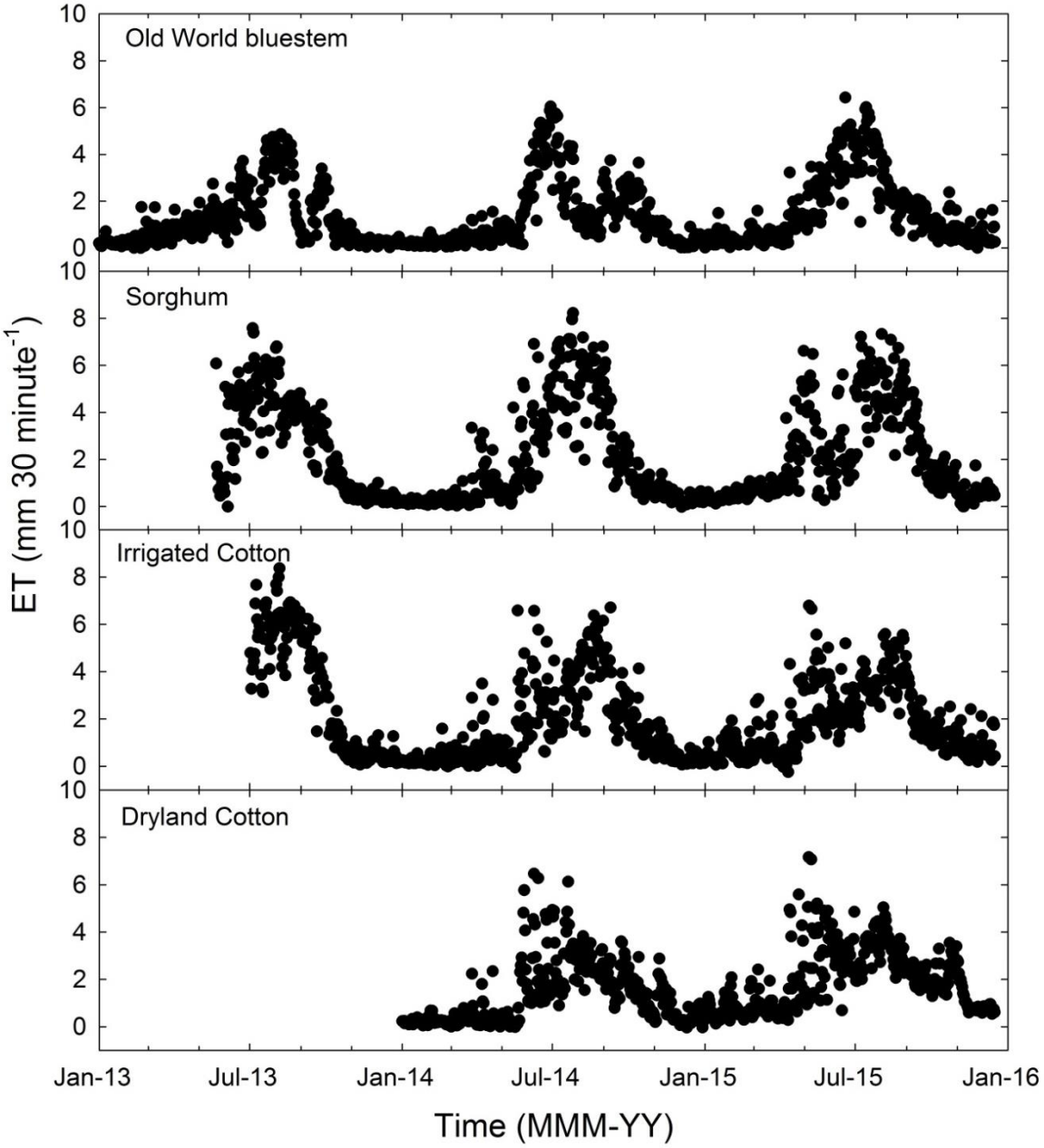


**Figure 5.3. Daily evapotranspiration for the complete study period. Old world bluestem had all three years of data, whereas data collection from irrigated crops started following planting in 2013. Dryland cotton crop failed due to lack of rainfall in 2014, thus the data was lost during that year.**

**Table 5.1. Seasonal and annual evapotranspiration and rainfall in different crops.**

| | Crop | Seasonal ET | Seasonal Rainfall | Annual ET | Annual Rainfall |
|---|---|---|---|---|---|
| 2013* | | | | | |
| | OWB | 326.6 | 445.0 | 398.8 | 506.5 |
| | Sorghum | 495.4 | 241.3 | 580.5 | 261.4 |
| | Irrigated Cotton | 483.4 | 241.3 | 677.7 | 261.4 |
| | Dryland Cotton | - | - | - | - |
| 2014 | | | | | |
| | OWB | 383.8 | 450.1 | 443.0 | 520.9 |
| | Sorghum | 522.5 | 348.5 | 683.6 | 417.8 |
| | Irrigated Cotton | 397.9 | 181.4 | 583.1 | 417.8 |
| | Dryland Cotton | 307.3 | 308.9 | 470.1 | 518.3 |
| 2015 | | | | | |
| | OWB | 442.9 | 675.9 | 530.3 | 825.7 |
| | Sorghum | 423.2 | 205.5 | 734.6 | 747.3 |
| | Irrigated Cotton | 348.0 | 224.3 | 655.8 | 747.3 |
| | Dryland Cotton | 339.1 | 234.9 | 696.6 | 751.1 |
| Mean | | | | | |
| | OWB | 384.4 | 523.7 | 457.4 | 617.7 |
| | Sorghum | 480.4 | 265.1 | 666.2 | 475.5 |
| | Irrigated Cotton | 462.9 | 215.7 | 653.9 | 475.5 |
| | Dryland Cotton | 323.2 | 271.9 | 583.4 | 634.7 |

*For sorghum and irrigated cotton only data from planting to end of the year was available.

Once the growing season started, ET increased steadily with rising temperature and plant size to its peak in July and August during growing season. Mean seasonal ET for all crops is listed in Table 5.1. Despite shorter growing season sorghum registered greatest ET among all the crops. Cumulative ET ranged from 495.4 to 522.5 mm in sorghum, from 326.6 to 442.9 in OWB, from 348.0 to 483.4 in irrigated cotton, and 307.3 to 339.1 mm in dryland cotton. The cumulative seasonal ET reported in different

studies for all these crops and other bioenergy crops have been listed in Table 5.2. Our cumulative mean seasonal ET results for sorghum are in good terms with the average ET reported by Tolk and Howell, (2001) in the Texas High Plains for different irrigation treatments (Table 5.2). However, the mean seasonal ET of sorghum was lower than that reported by Wagle et al. (2016) for rainfed sorghum probably because of greater rainfall received in their study during growing season. Seasonal ET of OWB was greater than that reported by Wever et al. (2002) for temperate grassland in Canada, but was in good terms with those reported by Burba and Verma (2005) for tall grass prairie in Oklahoma. In our results, sorghum and OWB registered lower magnitudes of seasonal ET than those reported for maize, switchgrass and *miscanthus* reported in different studies listed in Table 5.3. Relatively greater irrigation in 2013 to cotton led to higher seasonal ET, which was well comparable to the ET values reported by Howell et al. (2004) for cotton under full irrigation in the Texas High Plains region. However, the ET values of irrigated cotton in 2014 and 2015 were comparable to those of dryland cotton in Howell's (2004) study despite irrigation. Also, ET in dryland cotton was smaller than those reported by Howell et al. (2004) for dryland cotton.

**Table 5.2. Seasonal ET for different bioenergy crops as well as cotton reported in different studies.**

| Author | Crop | Region | Irrigation | Seasonal ET (mm) |
|---|---|---|---|---|
| Tolk and Howell (2010) | Sorghum | Texas | Irrigation | 400-490 |
| Wagle et al. (2016) | Sorghum | Oklahoma | Rainfed | 553 |
| Wagle et al. (2016) | Switchgrass | Oklahoma | Rainfed | 652 |
| Hickman et al. (2010) | Switchgrass | Illinois | - | 764 |
| Hickman et al. (2010) | Miscanthus | Illinois | - | 954 |
| Hickman et al. 2010 | Maize | Illinois | - | 611 |
| Wever et al. (2002) | Temperate Grassland | Canada | Rainfed | 226-295 |
| Eichelmann et al. (2016) | Switchgrass | Canada | Rainfed | 562-598 |
| Burba and Verma (2005) | Prairie | Oklahoma | Rainfed | 480-607 |
| Howell et al. (2004) | Cotton | Texas | Dry | 356-415 |
| Howell et al. (2004) | Cotton | Texas | Deficit | 619-639 |
| Howell et al. (2004) | Cotton | Texas | Full | 739-775 |
| Suyker and Verma (2009) | Maize | Nebraska | Irrigated | 631 |

Figure 5.4 presents the diurnal patterns of ET in each month of the growing season for all crops. Similar to energy partitioning, monthly diurnal courses of ET were consistent in row crops, while ET in OWB lacked consistency. Peak half-hourly ET values were observed from 12:00-14:00 hours in all crops during all months of growing season. In sorghum, highest monthly ET rate was recorded in July and August during all growing seasons. Irrigated and dryland cotton registered peak monthly ET rate in August when plants were flowering. Diurnal trends of ET in irrigated cotton were generally comparable in June, July, and September. Similarly, diurnal trends of ET in dryland cotton were comparable in June, July, and September, though dryland cotton registered

lower peaks than all the other crops during the growing season. Despite August being the driest month in 2014 and September in 2015, no considerable reduction in ET was noticed. Infact, half-hourly ET rates in August 2014 were the highest in dryland cotton. Evapotranspiration rates declined in October in all crops as the plants were senescing.

In OWB, peak average monthly half-hourly ET was recorded in August in 2013, in June in 2014 and June and July in 2015. In 2013 and 2015, lowest ET was observed in October as the crops entered senescence. Unlike dryland cotton, lowest ET values were observed during drier months of May and August in 2014. These findings suggest ET of the OWB were more sensitive to precipitation than dryland cotton. These results are in good agreement with those of Rajan et al. (2014), Burba and Verma, (2005) and Wagle et al. (2014) that suggests role of precipitation distribution is important in ET dynamics of rainfed perennial grass systems. The drop in ET during drier months in OWB was in agreement with drop in carbon uptake during these months. However, neither drop in ET nor reduction in carbon was observed during similar dry months in dryland cotton (discussed later). These findings suggest that during dry period cotton managed to draw water from deeper layers.

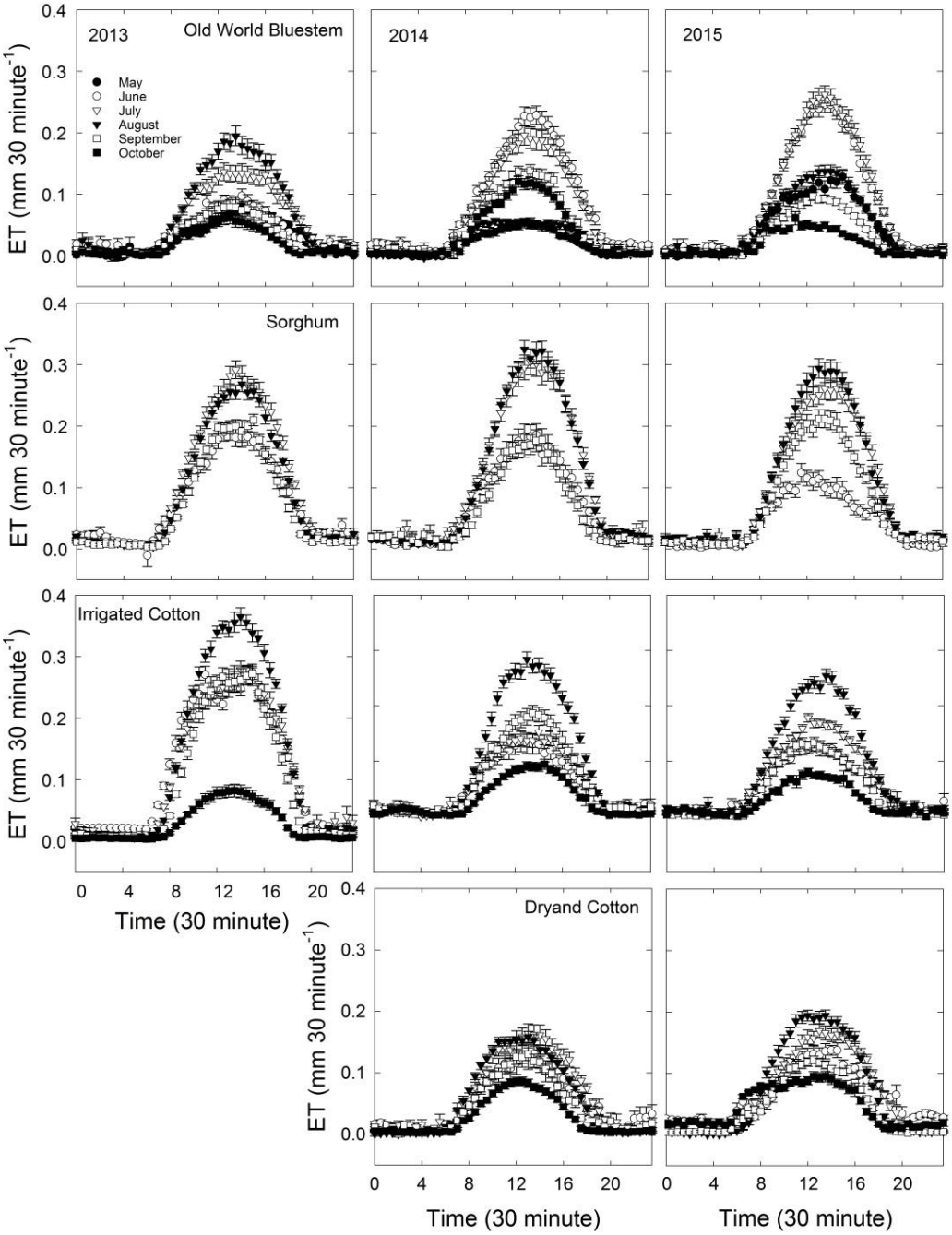


**Figure 5.4. Monthly diurnal patterns of evapotranspiration (ET) in different crops. Dryland cotton in year 2013 failed due to lack of rainfall, therefore we were unable to collect the data.**

Maximum mean monthly ET rate recorded in irrigated cotton was 0.36 mm 30 minute$^{-1}$ in August 2013, 0.28 mm 30 minute$^{-1}$ in August 2014, and 0.25 mm 30 minute$^{-1}$ in August 2015. Similarly, maximum mean monthly ET rate in sorghum was 0.29 mm 30 minute$^{-1}$ in July 2013, 0.33 mm 30 minute$^{-1}$ in August 2014, and 0.29 mm 30 minute$^{-1}$ August in 2015. In dryland cotton, Maximum monthly averaged ET rate was 0.16 mm 30 minute$^{-1}$ in July 2014 and 0.19 mm 30 minute$^{-1}$ in August 2015. In OWB, mean maximum monthly ET rate was 0.20 mm 30 minute$^{-1}$ in August 2013, 0.23 mm 30 minute$^{-1}$ in June 2014, and 0.26 mm 30 minute$^{-1}$ in July 2015.

**Environmental Controls**

Lower ET in non-growing season and higher ET during growing season suggest plant transpiration was dominant component in overall ET. In our results dynamics of ET during active growing season agrees with carbon uptake. For example, both ET and GPP were high at peak photosynthetic activity and low during drought. Carbon uptake by plants was sensitive to PAR under optimum moisture conditions for selected peak growth period (in chapter 3). Also, carbon uptake was limited with rising VPD during drier conditions in cotton and OWB. We plotted ET against PAR for selected clear days during peak photosynthetic activity (Fig. 5.5). For each crop, ET was a strong linear function of PAR for each crop. These results are in agreement with several other studies which have reported a strong dependence of ET on PAR (Wagle et al., 2016; Zha et al., 2013).

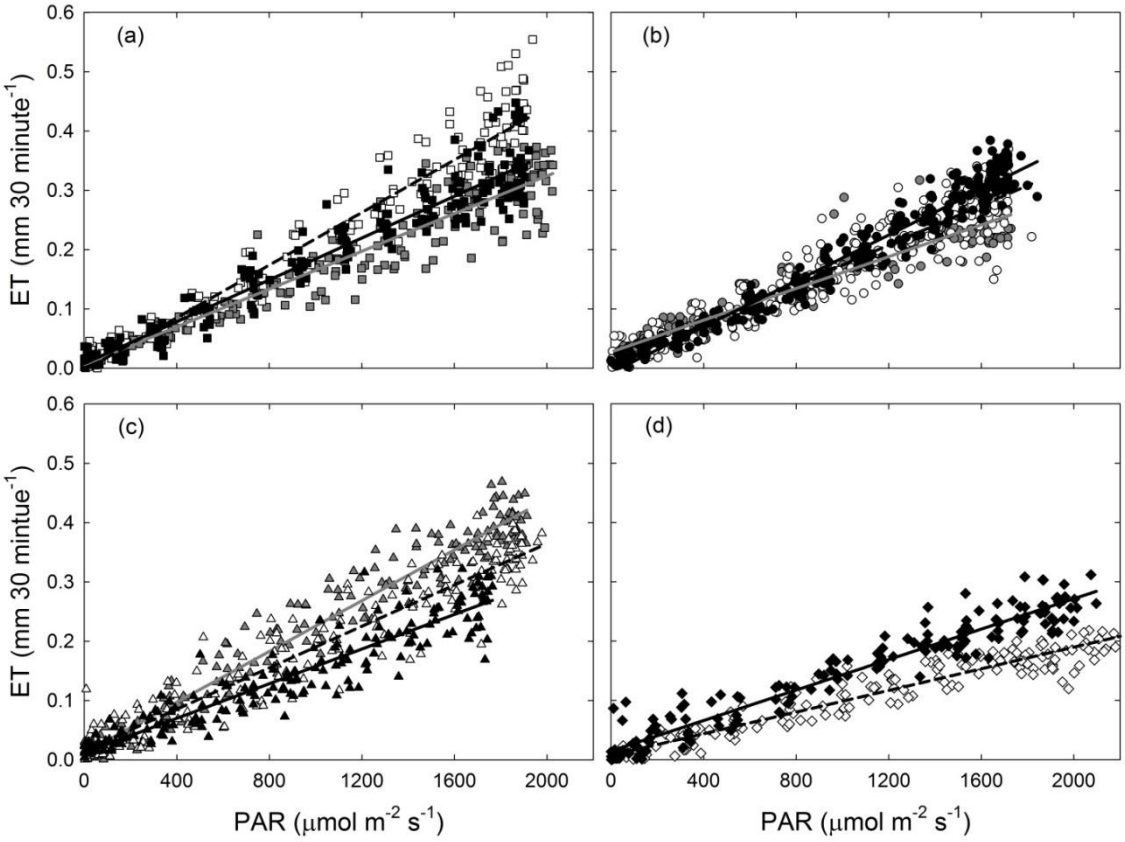


**Figure 5.5. Relationship between evapotranspiration (ET) and photosynthetically active radiation (PAR) for (a) sorghum, (b) old world bluestem (c) irrigated cotton (d) dryland cotton. Three-five consecutive clear days were selected during peak photosynthetic activity of growing season in 2013 (grey line), 2014 (dashed line), and 2015 (solid black line). Phenological stage was similar for each crop and soil moisture was > 0.20 $m^3$ $m^{-3}$. Each crop displayed peak photosynthetic activity during the selected period. All relationships were significantly linear ($p<0.0001$). All the $R^2$ values ranged from 0.88 to 0.94.**

## Water Use Efficiency

Water use efficiency calculated through different approaches is presented in Table 5.3. Ecosystem water use efficiency was comparable for each crop during all three

growing seasons. Sorghum (3.2-3.4 g C $kg^{-1}$ $H_2O$) and OWB (2.7-2.9 g C $kg^{-1}$ $H_2O$) being C4 plants registered greater seasonal EWUE followed by irrigated cotton (1.6-2.1 g C $kg^{-1}$ $H_2O$) and dryland cotton (1.3-1.5 g C $kg^{-1}$ $H_2O$). Our values of EWUE for sorghum are greater than those for rainfed sorghum (2.5 g C $kg^{-1}$ $H_2O$) reported by Wagle et al. (2016) in Oklahoma, but lower than EWUE of 3.8 g C $kg^{-1}$ $H_2O$ corn reported by Abraha et al. (2016) in Illinois. Ecosystem water use efficiency of OWB was lower than that of 3.3 to 4.1 g C $kg^{-1}$ $H_2O$ reported by Skinner and Adler (2010) for switchgrass in northeast United States, 3.6 to 3.8 g C $kg^{-1}$ $H_2O$ observed by Eichelmann et al. (2016) in Canada, and 3.1 g C $kg^{-1}$ $H_2O$ by Abraha et al. (2016). Lower EWUE of OWB in comparison to switchgrass in our study than the studies conducted in northern latitudes could be attributed to lower temperatures and VPD which lead to lower ET for equal amount of carbon uptake in Northern latitudes (Eichelmann et al., 2016). However, these values of EWUE fall within the range of 2.5-3.1 g C $kg^{-1}$ $H_2O$ observed by Wagle et al (2016) for switchgrass in Oklahoma. The EWUE of all the crops in our study fall within the range of EWUE reported by Beer et al. (2009) (2.1-4.4 g C $H_2O$) for grasslands and croplands. Comparable EWUE of OWB to switchgrass under similar environmental conditions (Wagle et al., 2016) suggests similar ecosystem productivity of OWB to switchgrass. This finding is important as similar ecosystem productivity suggests relatively equal sustainability of OWB in comparison to switchgrass in the Southern Great Plains in terms of water use efficiency. Also, it should be noticed that growing season length of the switchgrass in Wagle et al.'s (2016) study was at least a

month longer than OWB in our study, and therefore produced greater biomass than OWB.

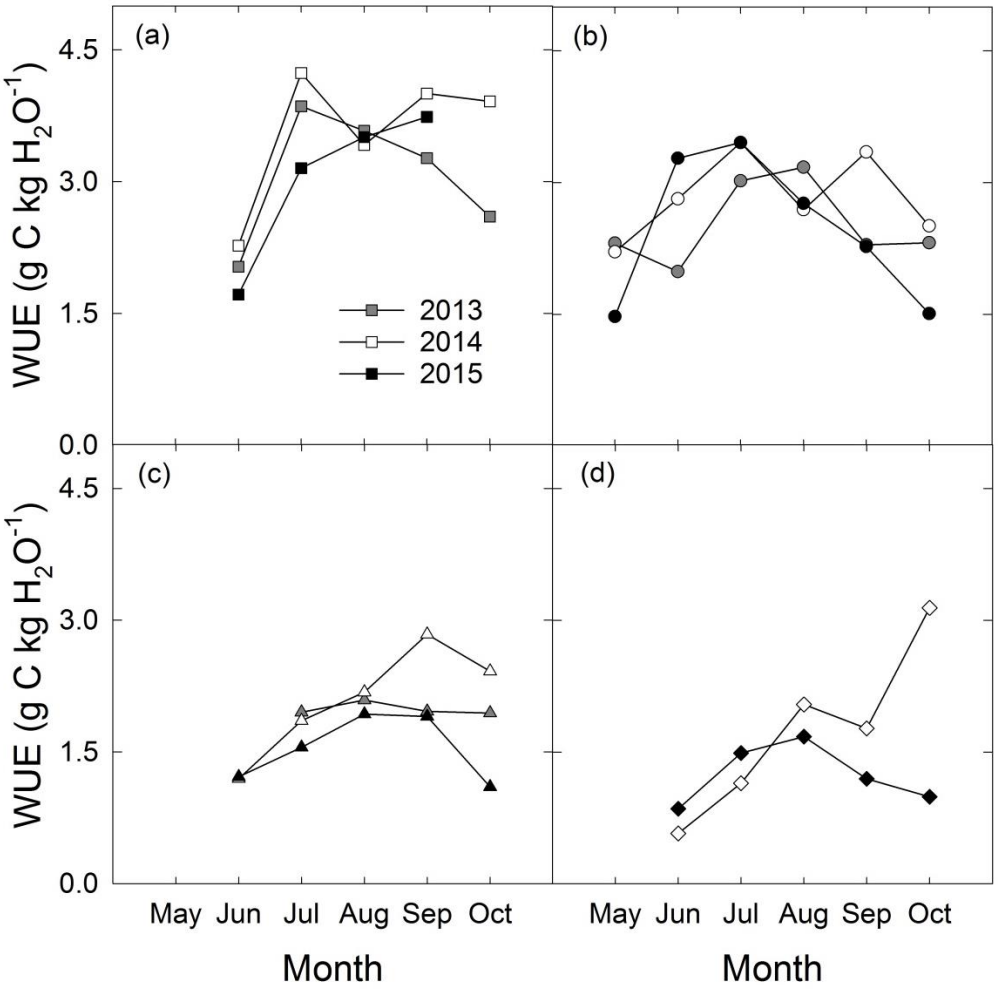


**Figure 5.6. Monthly water use efficiency for (a) sorghum (b) OWB, (c) irrigated cotton and (d) dryland cotton across 2013 (grey), 2014 (white), and 2015 (black). Monthly WUE was calculated by dividing monthly GPP (g C $m^{-2}$) with monthly ET (kg $H_2O$ $m^{-2}$). Only days before harvesting were selected during October.**

Monthly EWUE are provided in Fig. 5.6. It should be noticed that only those days were used of the last month when the crop (row crops) was still standing. Peak monthly EWUE for sorghum was observed in July in 2013 and 2014, and in September 2015. Irrigated cotton recorded highest EWUE in August in 2013 and 2015, and in September in 2014. In OWB, EWUE was highest during August in 2013 and in June in 2014 and 2015. In OWB, EWUE was smaller during dry month of June in 2013, and August 2014 and 2015. Dryland cotton registered highest monthly EWUE in August of 2014 and 2015. Ecosystem water use efficiency observed in final month of growing season was either comparable or higher than first month of growing season. These findings are in consistence with those of Wagle et al. (2014) and Skinner and Adler (2010) who reported greater EWUE towards the end of the season due to reduced ET. Once calculated the mean monthly EWUE was comparable to seasonal EWUE for the corresponding growing season in all crops.

The monthly WUE irrespective of the crop showed the trade-off between carbon uptake and ET, as ET was higher during high carbon uptake and low during low carbon uptake in all the crops (Vanloocke et al., 2010). Basically, months with lower GPP had lower WUE. This suggests while GPP declined during dry months, while ET did not decline. We plotted selected clear days from OWB, dryland cotton, and irrigated cotton from dry periods (Fig. 5.7). Normalized GPP values of these days were plotted against VPD on a logarithmic scale. The results showed that GPP declined after certain value of rising VPD (around 9:30 am, see chapter 3), however, ET remained high throughout this period. This suggests GPP is more likely to be affected by VPD then ET. Similar results

have been observed by Cabral et al. (2013) for C3 and C4 crops and Rana et al. (2016) for canary grass. The possible reason behind this could be added evaporation from soil and transpiration from cuticle during stomatal closure (Cabral et al., 2013).

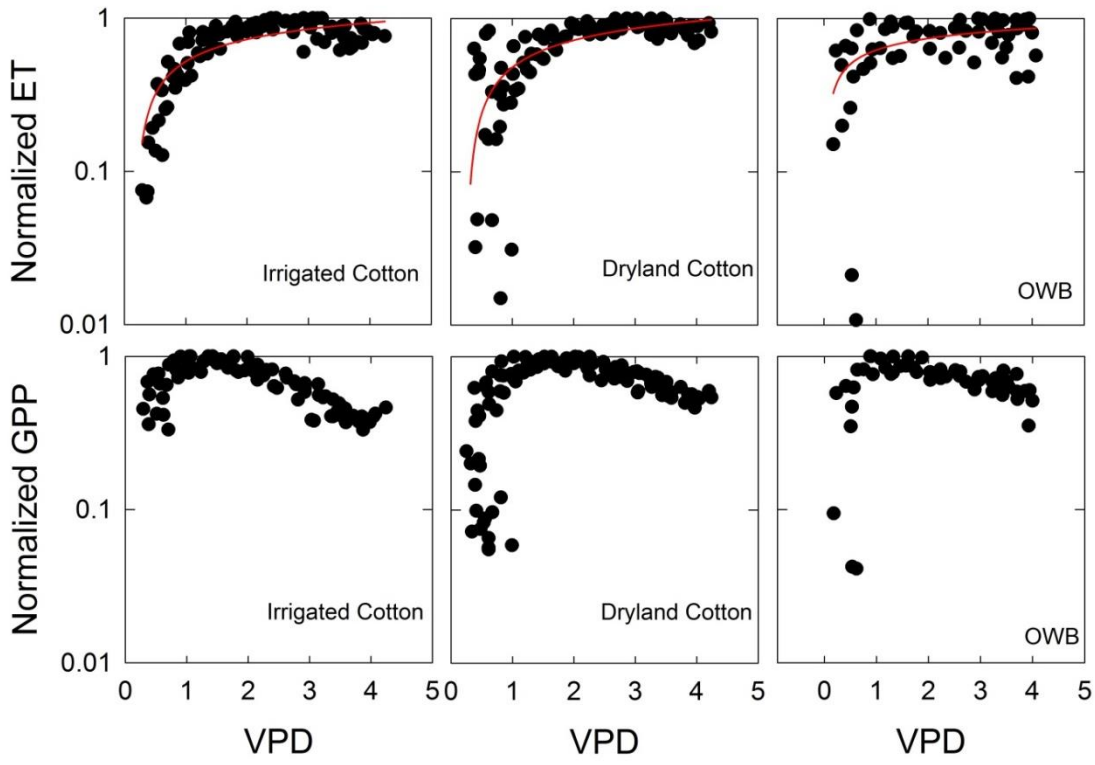


**Figure 5.7. Relationship of normalized evapotranspiration (ET) and normalized gross primary production (GPP) with vapor pressure deficit (VPD). Clear days during dry period were selected for this analysis (DOY 256-260 in 2015 for both irrigated and dryland cotton; DOY 224-227 in 2014 for dryland cotton). ET was a significant logarithmic function of VPD for all crops ($R^2$ = 0.67, 0.69 and 0.32 for irrigated, dryland cotton, and OWB respectively). GPP was not a strong function of VPD, except in dryland cotton ($R^2$=0.24).**

**Table 5.3. Seasonal ecosystem water use efficiency for different crops during different study years. Year 2013 does not represent the full cropping season for Irrigated Cotton as the data collection started about a month after planting.**

| Year | Sorghum | OWB | Irrigated Cotton | Dryland Cotton |
|---|---|---|---|---|
| 2013 | 3.2 | 2.7 | 2.0 | - |
| 2014 | 3.4 | 3.0 | 2.2 | 1.5 |
| 2015 | 3.2 | 2.8 | 1.7 | 1.3 |

Instantaneous water use efficiency calculated by obtaining linear relationships between monthly integrals of GPP and monthly integrals of ET across all growing season. Coefficient of determination and slope of each linear relation ranged from 0.82-0.97. Slope of this relationship represents the overall mean EWUE. Among all the crops, sorghum (4.5 g C $kg^{-1}$ $H_2O$) registered highest slope followed by OWB (3.8 g C $kg^{-1}$ $H_2O$), irrigated cotton (1.99 g C $kg^{-1}$ $H_2O$), and dryland cotton (1.4 g C $kg^{-1}$ $H_2O$). Water use efficiency of both sorghum and OWB was close, but greater than cotton. Being C4 plants sorghum and OWB have physiological advantages in terms of WUE.

**ET vs Rainfall**

Cumulative seasonal and annual ET data is presented in Table 5.1. Despite shorter growing season, annual row crops, especially irrigated crops registered higher seasonal ET than perennial grassland. Irrigated crops registered highest seasonal ET due to heavy irrigation during 2013 growing season followed by OWB. In 2014, sorghum registered highest seasonal ET, followed by irrigated cotton, OWB and dryland cotton. Old world bluestem registered highest seasonal ET in 2015, among all the crops. In general, seasonal ET of both irrigated crops was greater than seasonal rainfall. Greater

seasonal ET in OWB than dryland cotton was observed in both years, which could be attributed to longer growing season of OWB. Among non-irrigated crops, the share of ET in OWB was always lower than cumulative rainfall, than the share of ET in dryland cotton, which released similar or higher share of precipitation to atmosphere.

Similar to higher seasonal ET than seasonal precipitation in dryland cotton suggests most of the precipitation in dryland cotton crop was returned back to atmosphere through ET, leaving smaller portion of water available for groundwater recharge and runoff (Zeri et al., 2013). Although, determining surface runoff and drainage was beyond the scope of this study, previous researches have reported better infiltration capacity of water under established perennial grasslands than annual croplands due to improved soil health and percolation (Le et al., 2011; Bonin et al., 2012; Chen et al., 2016). This finding is in good terms with those reported by Chen et al., (2016) using model simulations for the South High Plains. Chen et al. (2016) reported improved annual percolation under land use change scenario where annual crops (cotton) are replaced with perennial (switchgrass) crops. This key finding from this research is important for future agricultural policies in the area, which will largely depend upon the status and recharge water table of the Ogallala aquifer.

In contrast, irrigated crops had higher seasonal and annual ET than seasonal and annual rainfall in first two years of study, respectively. The annual ET was lower in the 2015 for both irrigated crops but was still greater than average long term annual precipitation. Several researches have reported modification of climate with rising ET. For example, higher precipitation, lower temperatures, and an increase in thunderstorm

activity was reported following 120% rise in ET after conversion of croplands to steppe in Colorado (Pielke et al., 1998; Baron et al. 1998). Kueppers et al. (2007) reported reduction in air temperature due to enhanced evapotranspiration with increase in irrigation intensity in California. These findings suggest higher ET from irrigated sorghum may have significant implications to local weather patterns, in case irrigated sorghum replaces conventional cotton cropping systems. A similar conclusion can be made for irrigated cotton. However, with declining water table and regulation imposed by regulatory agencies in the high plains will be critical in shaping future scenario.

## CONCLUSION

Seasonal and annual energy fluxes, evapotranspiration, and water use efficiency at different scale was quantified for four different cropping systems during three different growing seasons. All years received annual rainfall similar to or higher than long-term annual rainfall. Energy partitioning was dominated by H during non-growing season in all cropping systems. Latent heat consistently dominated the energy partitioning in row crops during active growing season. Rainfall distribution and soil moisture played an important role in energy dispersal among H and LE in OWB. Ground heat flux remained a minor energy flux component during growing and non-growing season although some of the data was lost in non-growing season in row crops.

Our findings show greater productivity (EWUE) of the bioenergy systems over conventional cotton cropping system. The EWUE values of bioenergy crops in our study were in agreement with those reported for specific bioenergy crops in other studies. Greater productivity suggests higher sustainability of the bioenergy cropping systems

than cotton. However, due to irrigation sorghum crop shared higher seasonal and annual ET than seasonal and annual rainfall, respectively. Similarly, dryland cotton shared almost similar or higher seasonal ET than the seasonal rainfall. In contrast, seasonal and annual ET of OWB was lower than seasonal and annual rainfall. These findings suggest, OWB has potential of greater percolation and water conservation due to improved soil conditions and insulation provided by litter, whereas dryland cotton has potential to draw water from deeper layers. Long-term effects of these findings need further investigation, as the region of this study is susceptible to periodic droughts, which were absent during the period of this study.

# CHAPTER VI

## SUMMARY AND CONCLUSION

Current legislative and regulatory mandates aiming at reducing dependence on foreign oil imports has driven the rising bioenergy crops production in the United States. The Southern Great Plains have potential to grow bioenergy crops, however the implication of large scale production of bioenergy crops on carbon, energy and evapotranspiration (ET) balances of the region are not understood. Therefore, a study was conducted to assess and compare the carbon, ET and energy balance dynamics of two potential bioenergy crops with conventional cotton cropping system in the Southern Great Plains. Sorghum was the potential candidate of annual bioenergy crop and Old World Bluestem (OWB) was the perennial bioenergy crop. These crops were compared with irrigated and dryland cotton in the region. All the crops were managed by producers which gave us an opportunity to conduct research in standard production conditions followed in the region. Sorghum was irrigated while OWB remained dryland. The producer practiced annual crop rotation between irrigated cotton and sorghum on adjacent fields. Continuous measurement of carbon dioxide, ET and energy fluxes were made in each field using eddy covariance systems. In addition, meteorological variables

including rainfall, air temperature, photosynthetically active radiation, soil temperature, soil moisture, net radiation, soil heat flux, relative humidity, and vapor pressure deficit. All crops were net sinks of carbon at seasonal scale. Being C4 plants, bioenergy crops exhibited higher growth rates and greater carbon uptake potential than irrigated and dryland cotton, which is a C3 plant. Among the bioenergy crops, sorghum recorded greater carbon uptake than OWB at seasonal scale. This was also manifested in greater maximum above ground biomass production in sorghum (18-25 tons $ha^{-1}$) than OWB (7-10 tons $ha^{-1}$). Irrigated cotton on the other hand, was a greater sink of carbon in 2013 due to higher irrigation levels in that year, while it remained a weak sink in 2014 and 2015. Previous crop's residues contributed towards greater carbon release from the soil which reduced the net carbon uptake. Dryland cotton field failed in 2013 due to extended dry conditions during early months of growth, however field was a weak sink in 2014 and 2015 growing seasons.

On annual scale, sorghum was stronger (-445 g C $m^{-2}$) sink in 2014 while it remained a weak sink (-51 g C $m^{-2}$) in 2015. Irrigated cotton remained a net source of carbon (101 g C $m^{-2}$ in 2014 and 123 g C $m^{-2}$ in 2015) on annual scale, while dryland cotton was a net sink in 2014 (-19 g C $m^{-2}$) and a net source (59 g C $m^{-2}$) in 2015. In contrast OWB remained most consistent carbon sink throughout the study, with annual net carbon uptake ranging from -301 g C $m^{-2}$ in 2013 to -266 g C $m^{-2}$ in 2014. Non-growing season carbon release to atmosphere was higher in 2015 in comparison to 2014, due to relatively wetter winter in 2015, which may have triggered higher heterotrophic respiration in 2015 with rising temperature. This explains the lower sinking capacity of

the row crops in 2015 which led to lower annual carbon sinking capacity in row crops than in 2014. Similar, observations were noticed in OWB, greater carbon uptake in 2015 following higher rainfall kept the net carbon sinking of field comparable to other two years. As such, OWB remained the most stable carbon sink among all the crops in this study.

The available energy (net radiation) distributed among soil heat flux, latent heat and sensible heat. Across all the cropping systems, major part of the energy was distributed among latent heat and sensible heat. Latent heat represents energy lost for system in form of water and sensible heat represent the energy lost to atmosphere in form of heat. Apparently, latent heat dominated the energy partitioning in sorghum and irrigated cotton, as crops were irrigated regularly. In contrast, the energy partitioning switched from latent heat to sensible heat in OWB during dry periods of the growing season. Such, patterns were not noticed dryland cotton during dry periods. This suggested that dryland cotton had access to water in deeper layers during dry period.

Finally, ET of irrigated crops was higher than those of dryland systems. When compared with seasonal and annual rainfall, irrigated crops had higher ET than cumulative seasonal and annual rainfall. Dryland cotton had evaporation higher or equivalent to seasonal rainfall, while OWB registered lower ET in comparison to seasonal rainfall. Evapotranspiration in dryland cotton was higher during dry period than OWB. This suggests that dryland cotton may have accesed the water in deeper soil layers during dry period. Although no runoff measurements were made in the fields, we speculate the balance of water in OWB may have percolated in the soil indicating groundwater

recharging capcity of perennial bioenergy crop. On annual scale both dryland cotton and OWB registered lower ET than annual rainfall. Further, we calculated ecosystem water use efficiency (EWUE) of all the crops. Sorghum registered highest EWUE (ratio of seasonal gross primary production to seasonal ET) ranging from 3.2-3.4 g C $kg^{-1}$ water, followed OWB (2.7-3.0 g C $kg^{-1}$ water), irrigated cotton (1.7-2.2 g C $kg^{-1}$ water) and dryland cotton (1.3-1.5 g C $kg^{-1}$ water).

From the assessment of inter-annual and seasonal on-site carbon, ET and energy budget of all the these crops wecan make following conclusions.

1. Photosynthetic activity of sorghum are considerably affected by phenology (row spacing and LAI) and growing season length.
2. Higher growth rates of bioenergy crops make them robust on-site carbon sinks at seasonal as well as annual time scales in comparison to irrigated cotton cropping system, which was source of carbon at both scales. Dryland cotton cropping system can switch between sink and source depending upon climatic factors. Therefore, land use change induced by bioenergy crops may be more sustainable in terms of carbon budget than cotton cropping systems.
3. Among bioenergy crops, sorghum had higher annual net carbon uptake (net ecosystem exchange) than OWB in 2014 and lower in 2015. These findings suggest that annual net ecosystem exchange of sorghum will be more sensitive to non-growing season carbon dynamics than OWB, NEE of dryland OWB will be more sensitve to magnitude and timing of precipitation. Also, inherited benefits of perennial OWB in terms of no-tillage and no nutrient application may add to

the benefits and sustainability of the system. However, sorghum will provide greater biofuel feedstock than OWB.

4. Water use efficiency of bioenergy crops was higher than those of cotton, indicating higher sustainability in bioenergy crops than cotton. Higher sustainability of bioenergy crops may be beneficial in the long run in terms of value of water spent on these crops.
5. Higher ET from sorghum and irrigated cotton than rainfall may not only have significant implications on future climate, but may also be detrimental for the Ogallala Aquifer. On the other hand, lower ET in OWB than cumulative rainfall is likely to enhance water recharging capacity of soils in the Southern Great Plains.
6. Higher seasonal ET in comparison to seasonal rainfall in dryland cotton than OWB, indicated that dryland cotton had access to water from deeper layers.

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